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STUDY OF THE THERMAL DESIGN AND PERFORMANCE OF STRAPDOWN GUIDANCE AND CONTROL SYSTEMS

By John H. Sununu

MAY 1970

Prepared under Contract No. NAS 12-2143 by
JHS ENGINEERING CO.
Salem, New Hampshire

Electronics Research Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

This study was conducted under National Aeronautics and Space Administration Electronics Research Center Contract NAS 12-2143. The effort called for under this contract required engineering services to assist in the mechanical and thermal analysis of three distinct strapdown inertial sensing unit assemblies being designed and assembled at the Electronics Research Center.

One of the three design efforts was the analysis and review through fabrication of a prototype strapdown ISU utilizing laser gyros. The mechanical design of this system included implementation of a computer analysis to predict critical vibration frequencies and modes of the system, including the effect of the mechanical dither inherent in laser gyro systems. The thermal analysis included design of the structure, mounting techniques and establishment of specifications for the temperature control loops. A test program was also established for the evaluation of the thermal and mechanical performance of the unit.

The second system evaluated in this study was the SRT/IMU. This unit had been assembled prior to the study. However, the effort included specific redesign and refit recommendations to allow the system to be integrated within a flight test package for evaluation. This thermal interfacing included redesign of the thermal control system to permit flight testing without the Variable Thermal Impedance which was originally within the system.

The third system analysis consisted of a design review and establishment of test criteria for the ERSA/IMU. This system is a redundant inertial sensor IMU. Preliminary predictions were made for the change in thermal conditions which would result from single or multiple inertial component malformations.

This report summarizes the mechanical and thermal analysis

which supported the design and/or redesign of each of these prototypes to produce flight worthy hardware for the three systems. It should be noted that in this effort the contractor served in an advisory capacity and therefore the Technical Monitor was a major contributor to the system designs.

INTRODUCTION

The principal objective of this effort was to provide engineering assistance in the thermal and mechanical design of three different strapdown inertial sensing units. Each of these ISU's was a system research tool for the investigation of several innovations in strapdown technology. These systems were:

1. An ISU containing three Laser gyros which would be a flight worthy system for the evaluation of Laser inertial components.

2. The SRT/ISU which had already undergone preliminary testing and was now to be redesigned and reworked for flight testing of such concepts as interchangeability of inertial components.

3. The ERSA/ISU which was designed to evaluate the capabilities and advantages of using redundant inertial components.

For each of these systems, long term dimensional stability was a major objective.

THERMAL DESIGN OF STRAPDOWN SYSTEMS

General.--One of the more significant inherent advantages of a strapdown system is that the IMU can be designed so that virtually all of the thermal paths from the critical sensors to the environment are conductive paths. Thus, all thermal performance dependence is shifted away from the relatively unpredictable convective and radiative modes of heat transfer. Wherever possible all potential spurious thermal paths involving either of these modes should be eliminated from the design.

Since all the sensors are to be mounted on a common block, the thermal control problem will be considerably simplified if all sensors are operated at the same nominal temperature.

If the sensors were to operate at a temperature difference of 10°F, for example, (150°F gyros and 140°F accelerometers), the thermal control power required to keep the gyros hotter would be high unless there was a relatively large thermal resistance between the gyros and the accelerometers. Since all sensors are generally mounted on a common block made of high conductivity aluminum this large resistance could only be conveniently provided by an insulator between the gyros and the block, which is often not practical for the mechanical design.

In order to achieve reliable efficient control of the sensor temperatures to within ± 0.1°F under the broad range of potential ambient temperatures (30°F to 120°F), it appears that the thermal control system should be designed around individual thermal control systems, or at the least, a multi-zone block control system. For systems with a design requirement for removable sensors, with the resulting inherent uncertainty in the thermal resistance from sensor to block, preference should be given to the selection of individual sensor thermal control. (A simple comparison of multiple control systems versus a single block control system is included in Appendix B.)

If all the sensors are operated at the same nominal temperature, it is apparent that the thermal path from each sensor through to the common sensor block should be a relatively low resistance conductive path, with the associated metal to metal interfaces. In order to minimize the thermal control power it is desirable to have a relatively high thermal resistance between the control surface and ambient. The proper place for this high thermal resistance appears to be between the sensor block and the structure.

For missions with a narrow band of possible ambient temperatures, a simple high resistance interface plate (glass, quartz, micalex, etc.) properly designed is the most practical approach. For missions with a relatively wide band of ambient temperature a variable or controllable thermal resistance will reduce the thermal control power required

The least reliable and most difficult to predict thermal paths of a Strapdown System are the resistances of the many interfaces between sensors and the environment. In order to reduce the magnitude of the potential uncertainty in true thermal resistance from sensor to environment these interface resistances should be made as small as possible relative to the overall resistance.

A requirement for removable sensors makes the interfaces associated with the sensor mounting the most sensitive to these variations. Since interface resistances are inversely proportional to the contact area, they often are designed to have substantially larger surface than might be dictated simply by mechanical requirements.

LASER GYRO ISU

General objective.--In order to evaluate the performance and limitations of a guidance and navigation system in which the conventional electromechanical gyros were replaced by electro-optical (Laser) components NASA ERC decided to construct a three axis strapdown ISU using three Honeywell GG 1300 Laser gyros. This prototype would be tested in the laboratory at ERC but would be designed as a piece of flight worthy hardware capable of eventual system evaluation in an actual vehicle. Preliminary data showed the Laser gyro to be relatively insensitive to the level of its operating temperature. In order to verify the effect on overall performance the system would be designed to be capable of operating at more than one block set point temperature. Thus a data base for the system could be obtained for the limits of applicable environmental temperatures.

Design constraints.--Volume: The Laser ISU was designed as such that the system could be mounted and tested in the existing equipment available. This limited the overall dimensions to 14" x 14" x 14".

Mounting: Within the limitations of the other constraints, the mounting arrangements should be as close as possible to the center of gravity of the system to minimize any cross coupling effects arising from the dynamic response of the structure.

Operating Temperature: Since the system would be eventually operated in an uncontrolled flight environment, the system should be capable of operation at ambient temperatures from 30°F to 110°F.

Power: Minimization of temperature control power requirements was a high priority design objective.

Weight: In spite of the fact that the Laser gyros weighed almost 16 pounds each, the weight design objective for the complete system was 85 pounds.

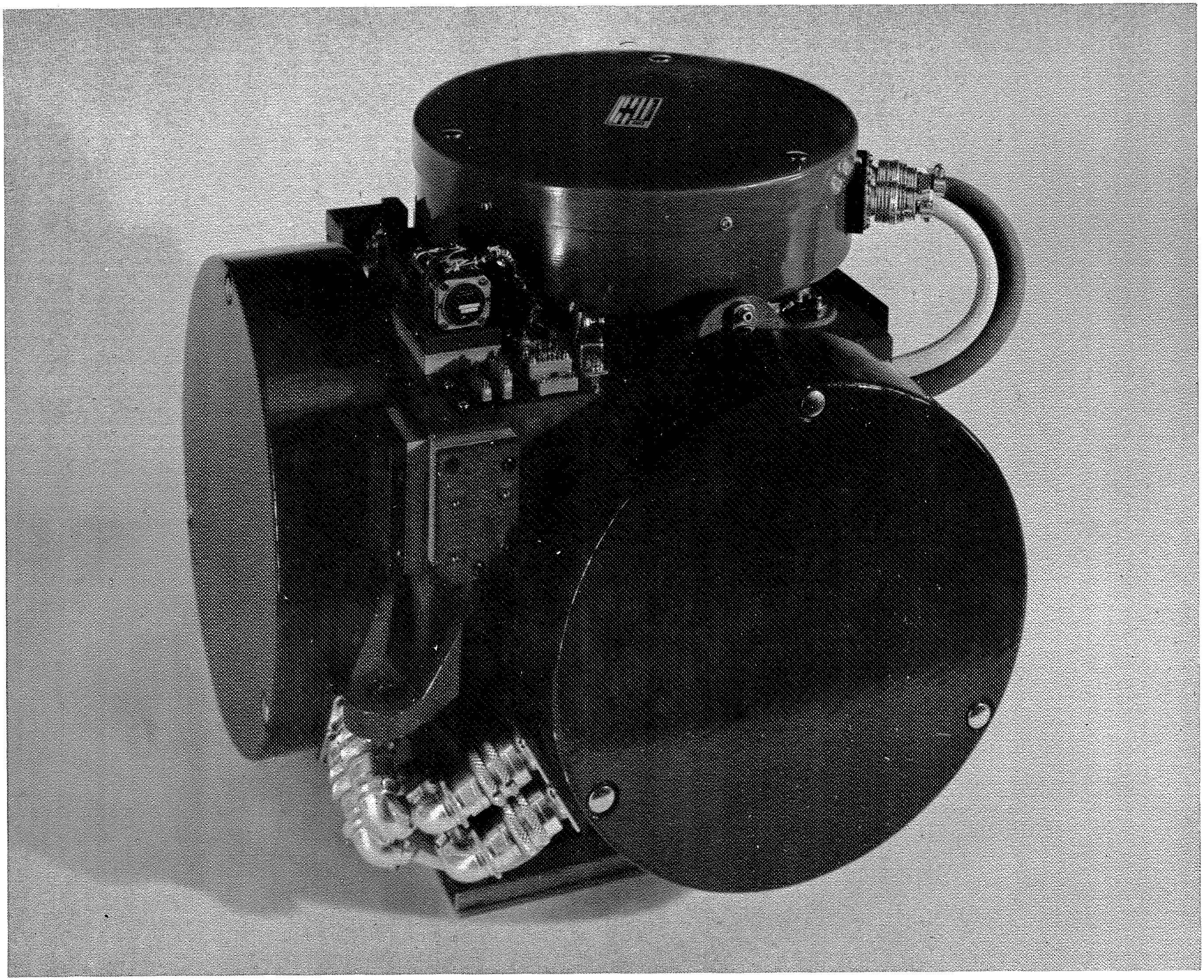


FIGURE I   Laser ISU with inertial sensors mounted.

Dimensional Stability: The system design, material selection and fabrication methods shall be selected so as to provide mounting surfaces which are coplanar to within .0002 ~~0.002~~ inches and orthogonality of the inertial components to the same order of accuracy.

SYSTEM DESIGN

General.--This section is a concise presentation of the design and the considerations involved in the principal design decisions for the Laser ISU. In some cases the details of computation have been included in the Appendices.

Block material.--In any strapdown ISU one of the principal considerations is the geometric stability of the sensor block. This stability is affected by material properties, fabrication techniques and operating conditions. On the basis of previous studies which considered properties such as long term dimensional stability, microyield strength, microcreep characteristics, thermal conductivity, the effects of machining, thermal expansion and density, it was decided that aluminum alloy would be the best basic structural material for fabrication of the block.

Because of the complexity of the mechanical configuration that was required a casting alloy was selected. Although both A356-T6 and Precedent 71A-T1 had excellent characteristics to meet the physical stability criteria, Precedent 71A-T1 was selected. This selection was made because of its better long term stability, although it was recognized that it is a relatively new alloy with little documented performance under various operational conditions.

Other materials used in the system included aluminum alloy 6061-T6 and stainless steel alloy 416.

The 6061-T6 was used in come of the detailed parts because its MYS of 26,000 psi is considerably higher than that of the Precedent 71A-T1 (approx. 10,000 psi). The use of stainless was principally dictated in those situations where a relatively low thermal conductivity was required by the thermal design.

Whenever extremely low conductivity parts were required Microid 750 was used. This was selected primarily because its thermal expansion coefficient is well matched to aluminum and therefore it can be used with good results to fabricate composite parts using these two materials.

Allowable stress levels.--The stress levels within the block were limited to 6000 psi to insure the dimensional stability of the system. In those areas where high contact stresses were to be expected stainless inserts were used to prevent local deformation. These inserts were rough machined and then bolted and pinned to the structure. The final tolerances were obtained by machining these pads in place on the block.

Heat treatment.--The heat treatment procedure for the Precedent 71A was selected to stress relieve the material to give best possible dimensional stability. These relief of stresses was followed by a hardening treatment to promote free machineability. The procedures are outlined in Appendix F.

Thermal design.--The thermal design of the ISU was developed in two separate phases. The first phase established the overall approach to assure that the system was capable of maintaining temperature or adequate rejection of power over the full range of ambient conditions. The second phase established the details of design required to provide the required temperature distribution throughout the system.

Since the prototype system was to be designed as a flight worthy unit capable of performing in ambient conditions ranging from 30°F to 110°F, it was decided that a fan and air-cooled cold plate assembly would be incorporated into the design as the mechanism for final rejection of power. This decision was dictated by the desire to minimize the thermal control power requirements under all conditions. The use of a fan and cold plate allows the nominal thermal coupling between the ISU and the environment to be varied simply by variation of the fan duty cycle from 0 (always off) to 100% (always on). The fan was attached to an annular vibration mount so as not to induce any vibration into the structure. This variation in coupling or thermal impedance can produce an appreciable reduction in the thermal control power required to maintain the block temperatures when the system is exposed to cooler ambients (see Appendix F). For the specific design requirements of the Laser ISU this resulted in a saving of the order of forty watts.

Although the Laser gyros were not very sensitive to small changes in block temperatures the accelerometers did require a maintainance of their operating temperature to

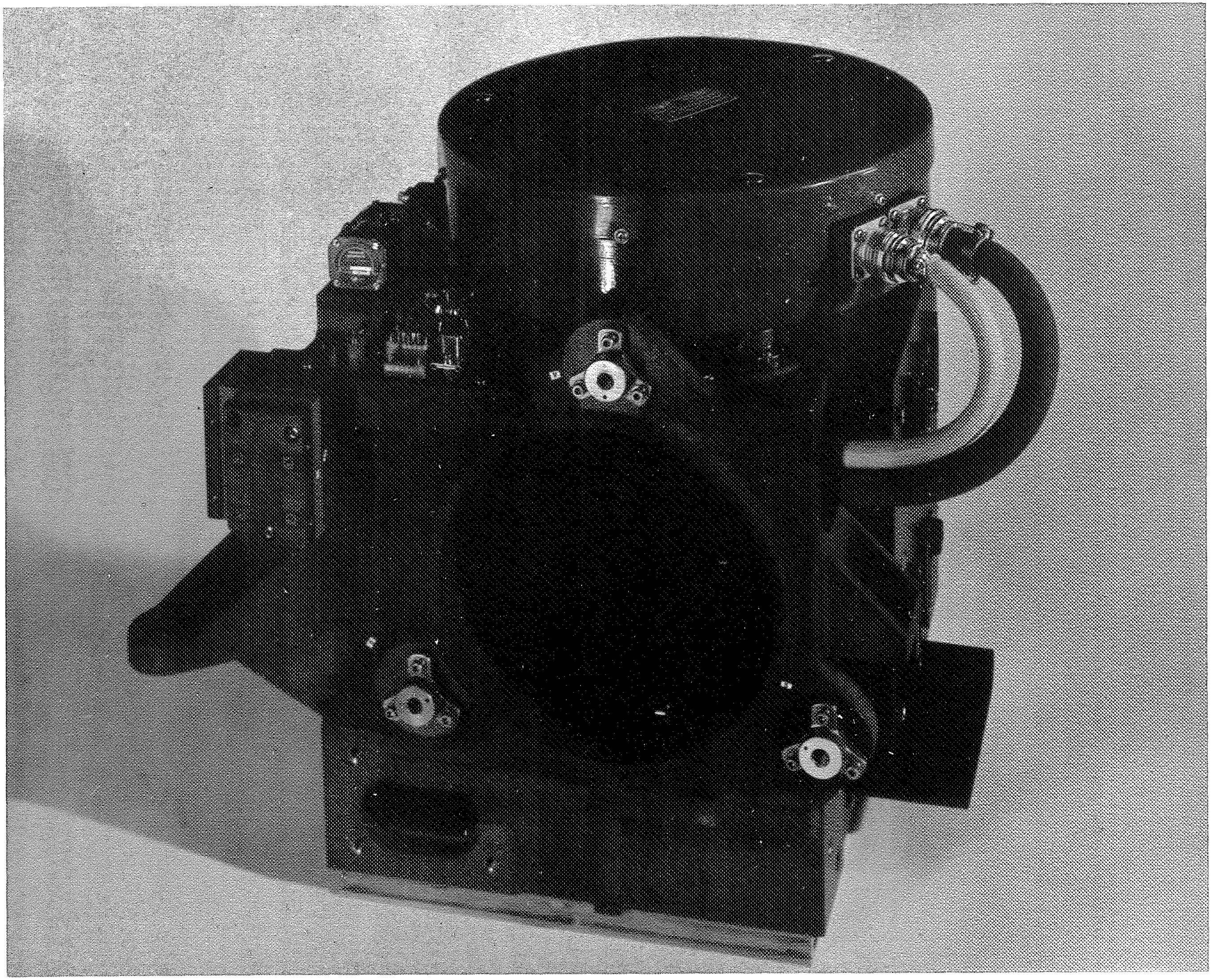


FIGURE II Laser ISU assembly showing mounting pads for components and platform C. G. mounts.

within $\pm$ .1°F. In order to achieve this it was decided that each accelerometer would have its own individual temperature controller, in addition to the main block controller. A separate block warm up circuit was also provided.

The necessary temperature distribution was provided by means of the detail design of the block and auxiliary hardware. The relation between the thermal and mechanical requirements of the system required a close cooperative effort in these design areas. In some of the areas of the block the material required to limit the stress and deflections, and maintain dynamic stiffness was more than adequate to meet the requirements for thermal performance. In a number of cases, however, the physical dimensions were dictated by thermal requirements. It was estimated that 20% of the weight of the casting was due to thermal requirements rather than mechanical considerations. A schematic of the major thermal impedances and a summary of the computations are included in Appendix G.

<u>Temperature control system</u>.--The principal components of the temperature control system were:

1. Three 5 watt accelerometer temperature controllers with input bridges, heaters and sensors (one for each accelerometer).

2. One 50 watt block temperature controller with input bridges, heaters and sensors.

3. One 750 watt block warm up heater with solid state control.

4. One 5 watt plate heater with solid state control.

5. One fan.

6. One finned aluminum heat exchanger.

The system was designed so that the 750 watt warm up loop was designed to actuate only during the start up mode. This loop was provided with fail-safe circuitry in order to prevent this heater from being activated during the control mode even if the temperature fell below the set point. The control system also had a manually insertable operating mode which cycled the fan. This operating mode turned the fan off whenever more than 45 watts of block temperature control heater power was called for.

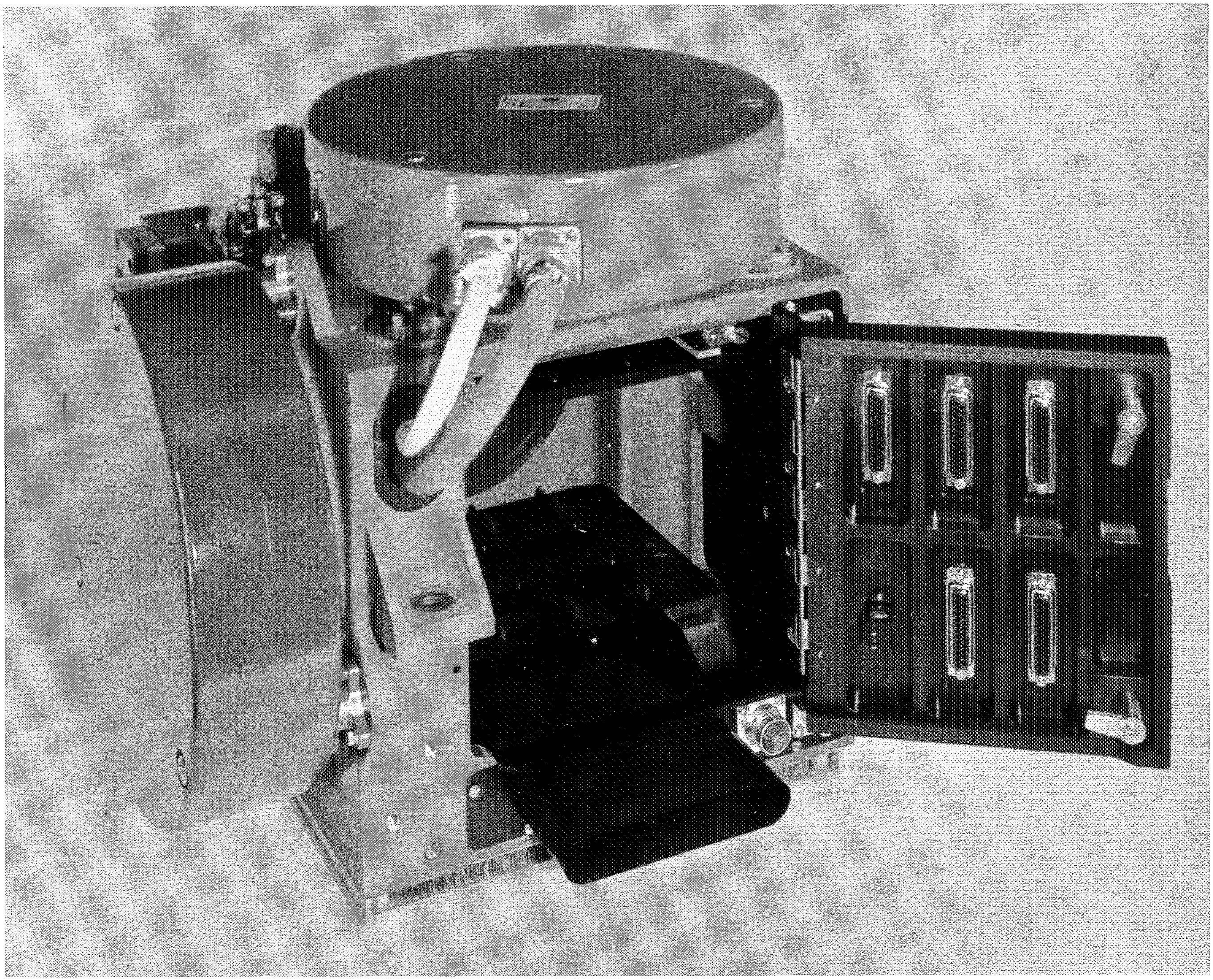


FIGURE III Laser ISU with access door to electronics compartment opened. Note the oval air inlet for heat exchanger fan assembly.

A summary of the specific component characteristics is shown in Appendix H, with the specification for the hardware for the Temperature Control System.

Structural design.--The block and all of the system hardware elements were modeled as a discrete mass, elastic system using a finite element representation. Using a digital computer program, the response of this system under dynamic loading conditions was examined. This study included an examination of the free vibration response of the entire system and of the effect of the Laser gyro "dither" as a force input on the block.

An initial simulation of the system including the Laser gyros as concentrated masses predicted the first two resonant frequencies as 247 Hz and 387 Hz. The mode corresponding to the lowest natural frequency is sketched in figures 1 to 6 of Appendix D.

This model was refined to give a more accurate representation of the block and electronics without the Laser gyros, as shown in figures D7 to D12. In phase, sinusoidal forces, applied at the gyro supports were input to the model at discrete frequencies from 1 Hz to 500 Hz. Typical displacement responses to these input forces are indicated in figures D13 through D18. The ratio of displacement amplitude at the dither frequency, 113 Hz, to the response for the same force at 1 Hz is indicative of the dynamic effects. The first natural frequency was 206 Hz.

General configuration.--The design constraints and the physical size and weight of the Laser gyros virtually dictated that the block be essentially cubic. Consideration of the overall system weight and storage requirements for hardware resulted in a casting design which consisted of a hollow six-sided box with wall openings and an attached "door" to allow for easy insertion and removal of the electronics.

The clock and rebalance loops were mounted on a removable aluminum plate on which there was located a separate temperature control heater with its own control loop. This plate was isolated from the block by either of a pair of insulator sets, depending on which end of the range ambient temperatures the system was operating. This discretely variable thermal impedance conserved thermal control power in a manner analogous to the continuously variable impedance. Calculations for the required thermal resistances are shown in Appendix G.

The principal mounting surfaces consist of three surfaces located 120° apart at the plane located at the C. G. of the system. On the lower surface of the casting is attached the

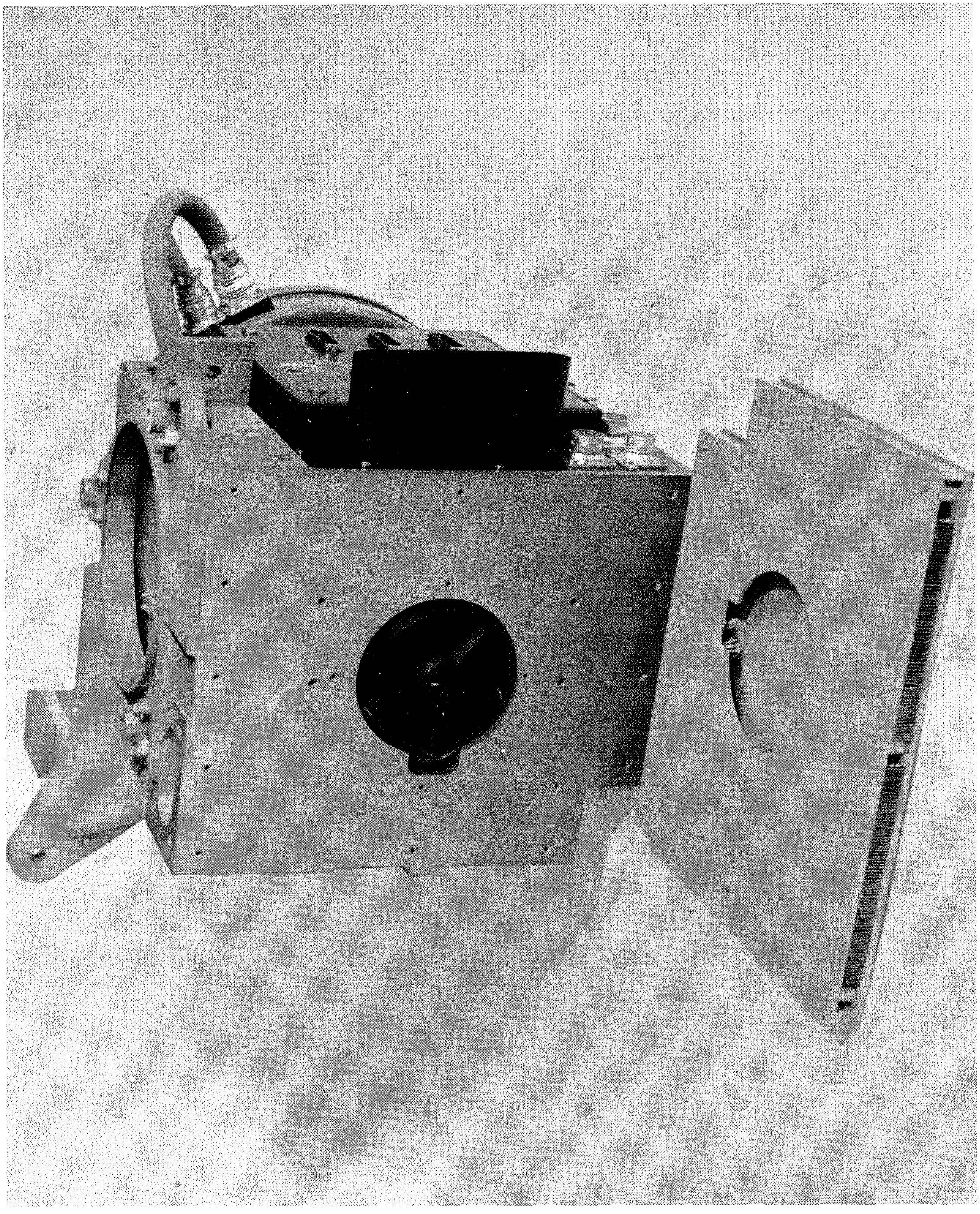


FIGURE IV Bottom view of Laser ISU with heat exchanger disconnected showing the location of fan.

fan and heat exchanger assembly which serves as the principal mechanism for the rejection of power.

Pictures of the system are shown in Figure 1-4.

Single unit test station.--In order to evaluate and exercise a representative Laser gyro at various operating temperatures, a single unit test station was designed and assembled. The system was designed for use in the laboratory and was not intended to serve as anything other than a thermal exercise station for evaluation of the inertial component. The thermal schematic of the unit is shown in Appendix I with design sketches and photographs of the unit as fabricated.

Temperature control subsystem for electronics mounting plates.--In order to minimize the temperature control power that would be required to maintain temperature of the electronics mounting plate at the required 130 $\pm$ 5°F over the two very different block temperatures to be exercised, a discretely variable impedance was designed into the system. The plate was designed to hang from a track and be isolated thermally from the block by means of Microid mounting pads. This would allow the system to maintain temperature when the system was being operated with an 80°F block. If the block was being run at 130°F the design included a set of stainless steel thermal shunts to short circuit the system. The calculations for the required thermal resistances and control power are shown in Appendix G & H.

SRT/IMU

General objective.--The SRT/IMU was originally constructed for NASA ERC as a flexible, breadboard system to be used for development of software and hardware technology. This system, as originally designed, included specific advancements such as interchangeable inertial components and a variable thermal impedance for the reduction of thermal control power requirements.

After the initial verification testing was completed ERC decided to conduct a series of flight tests using a helicopter as the test vehicle. It was also decided that the flight test would be performed without the variable thermal impedance originally utilized in the system. This required a temperature test program to determine the characteristics of the system without the VTI. Based on this data a redesign of the thermal impedances and thermal control

INERTIAL SENSING UNIT (ISU) - PICTORIAL VIEW

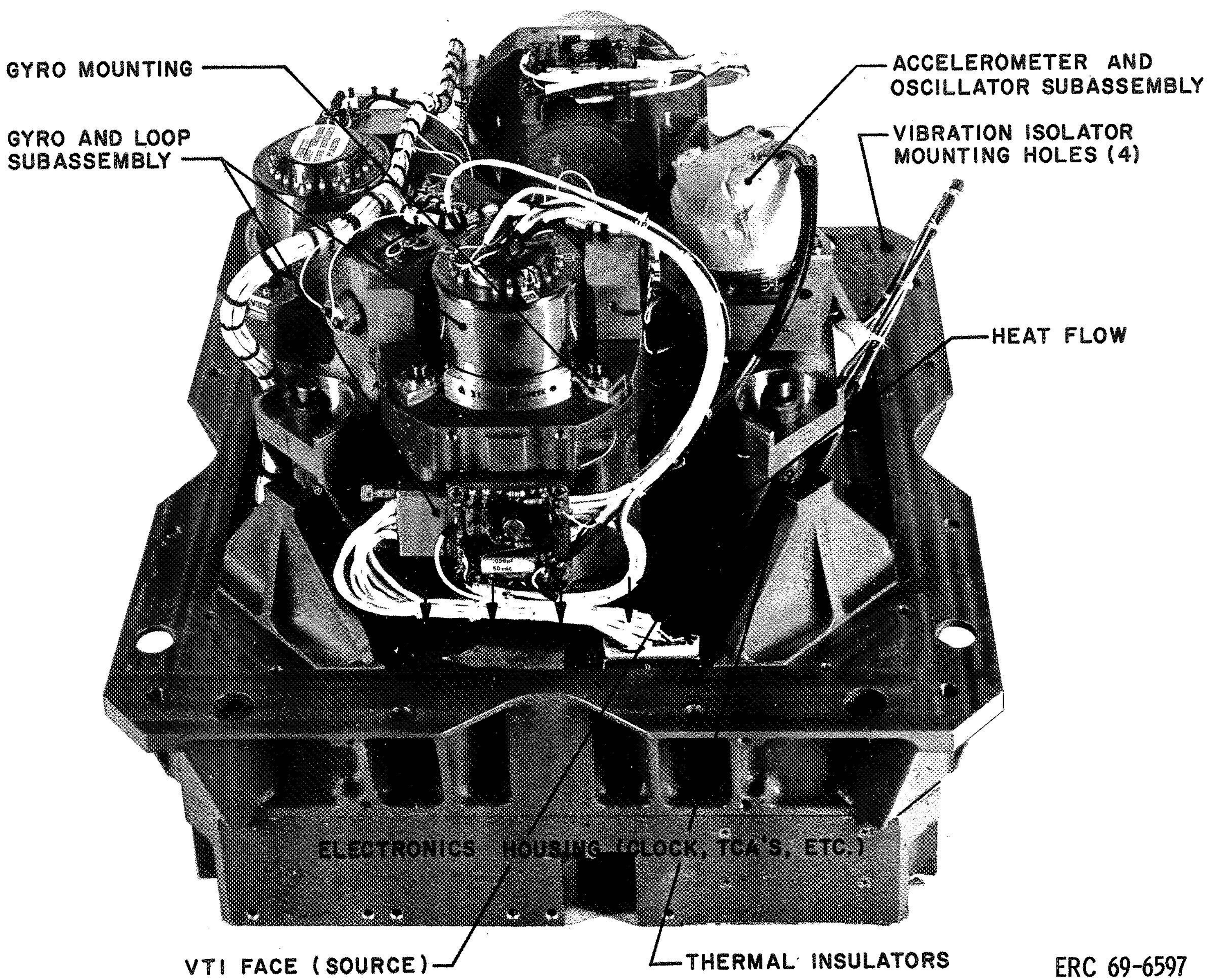


FIGURE V Early configuration of the SRT/ISU showing the principal components. The thermal redesign replaced the VTI with a thermal transfer plate and modified the accelerometer mounts.

system had to be performed.

This test program was performed at the Experimental Astronomy Laboratory at MIT under NASA Contract NAS 12-2085. These test activities were coordinated with the analysis effort and the experimental results incorporated into the system redesign. A complete summary of the results of this test effort is contained in the MIT Report RN-59, "Temperature Readout System for Strapdown Gyros" by J. T. Egan, May 1970.

Design Requirements

Effective ambient temperature.--$80^{o}F$ to $100^{o}F$ at the mounting flange.

Thermal control power.--Less than 75 watts, including control of electronics.

Preservation of C.G.--Since the system was designed with a C.G. mounting configurations, any alterations must be achieved without affecting the location of the C.G.

Inertial components.--The gyros would be the same as the original design. The accelerometers would be changed from the D4E units originally used to the 2401 series. This necessitated a redesign of the adapter and compensation for the thermal resistance associated with accelerometer mounting.

Housing for electronics.--The mounting compartment for the electronics had to be redesigned to accommodate the new system specifications for flight testing. This subsystem also had to be interfaced with the thermal design of the ISU itself.

System Redesign

General.--This section describes the test program reviewed and the redesign effort carried out in order to convert the SRT/IMU to a flight worthy system for tests aboard a helicopter.

Test program.--This effort evaluated the test and verification program established by ERC at the MIT Measurement & Systems Lab to determine the thermal performance of the SRT/IMU. The test equipment and facilities were examined; recommendations for the tests and exercises were also made. The data was examined and using this material the significant performance parameters of the system were calculated.

Specifically the direction and supervision included the following:

1. Establishment of the objectives for the program.

2. Outlining a series of definitive tests.

3. Review and approval of the major test facilities.

4. Recommendations for simulation of the thermal environments.

Redesign of inertial component mounting.--The accelerometers selected for the flight test of the SRT/IMU were not identical with those chosen for the initial design. As a result it was necessary to design a mating adapter for the new accelerometer to provide both mechanical compatability and to compensate for the different thermal resistance necessary to accommodate the different level of power dissipation.

Redesign of thermal shroud.--The original design specifications for the SRT/IMU required the system to be contained within a 12" x 12" x 12" cube. This constraint limited the adequacy of the thermal shroud designed for the system. The space requirements for the flight test were considerably less stringent, and therefore, a more effective shroud could be designed. Rather than merely deliver material and dimensional requirements for this unit, a set of trade offs between thermal control power and shroud design were presented. The final design as selected by the technical monitor represented an optimization of the various alternatives. The values used for comparison are shown in Appendix J.

Redesign of heater and control system.--The temperature control system of the SRT/IMU was never finally trimmed to optimize the temperature distribution across the block. The test and verification program provided a date base for this and the block heater resistance values were timed to give the correct temperature at all the inertial components at 110°F environmental temperature. Using this established heater profile it was recommended that the temperature distribution at other effective environmental conditions be measured to obtain data on the range of deviations of the block temperatures that might be expected. These tests were conducted by MSL and indicated that the combination of block and component temperature control systems are capable of holding the component temperatures to the desired levels.

Replacement of VTI.--The SRT/IMU as orginally designed included a variable thermal impedance as one of the major components in the thermal control loop. (An analysis of the thermal control power that can be saved by using a VTI is calculated in Appendix C). The system as delivered failed to accomplish the thermal control power savings that had been anticipated in the design. Furthermore, the VTI as a piece of hardware proved to be somewhat tempermental and unreliable. It was also determined by analyzing both the test data from the SRT/IMU contractor and the data from MSL, the trouble was due to parasitic thermal losses which were due to "squeezing" the design due to space constraints. Since these design difficiencies could not be easily eliminated, it was decided to replace the VTI with a fixed resistance interface plate. Proper design of this plate required a correct set of values for the thermal resistances of the system, especially those which coupled the system to the environment.

<u>Determination of thermal resistances</u>.--The experimental results of the contractor test program and the MSL tests were used to calculate the principal thermal resistances of the SRT/IMU. The latest results of these calculations have been included in the material of Appendix K.

This information was then used to design a replacement fixed resistance for the VTI of the original design. This replacement resistance was designed so that the value of its impedance could easily be varied and trimmed, if desired, if preliminary system tests of the flight hardware indicate that this would be advantageous.

<u>Interfacing of the SRT/IMU</u>.--Once the redesign of the system was accomplished it was interfaced with the hardware of the system pallet. The compromise specification was to establish a mounting flange temperature requirement for the pallet temperature control system of 80°F to 100°F for all ambient temperatures from 30°F to 120°F. These requirements appear to be well within the capabilities of the pallet system being assembled.

<u>Thermal design for the electronics</u>.--The electronics subsystem had to be redesigned to handle the redesign of the ISU thermal control system, particularly since there would no longer be a VTI to isolate the system from any temperature swings of the environment. The required thermal resistances and power range for the temperature control subsystem is shown in Appendix L.

ERSA

<u>General objective</u>.--The ERSA system is a redundant sensor strapdown IMU designed at ERC investigate and analyze the advantages that accrue from utilizing more than the minimum

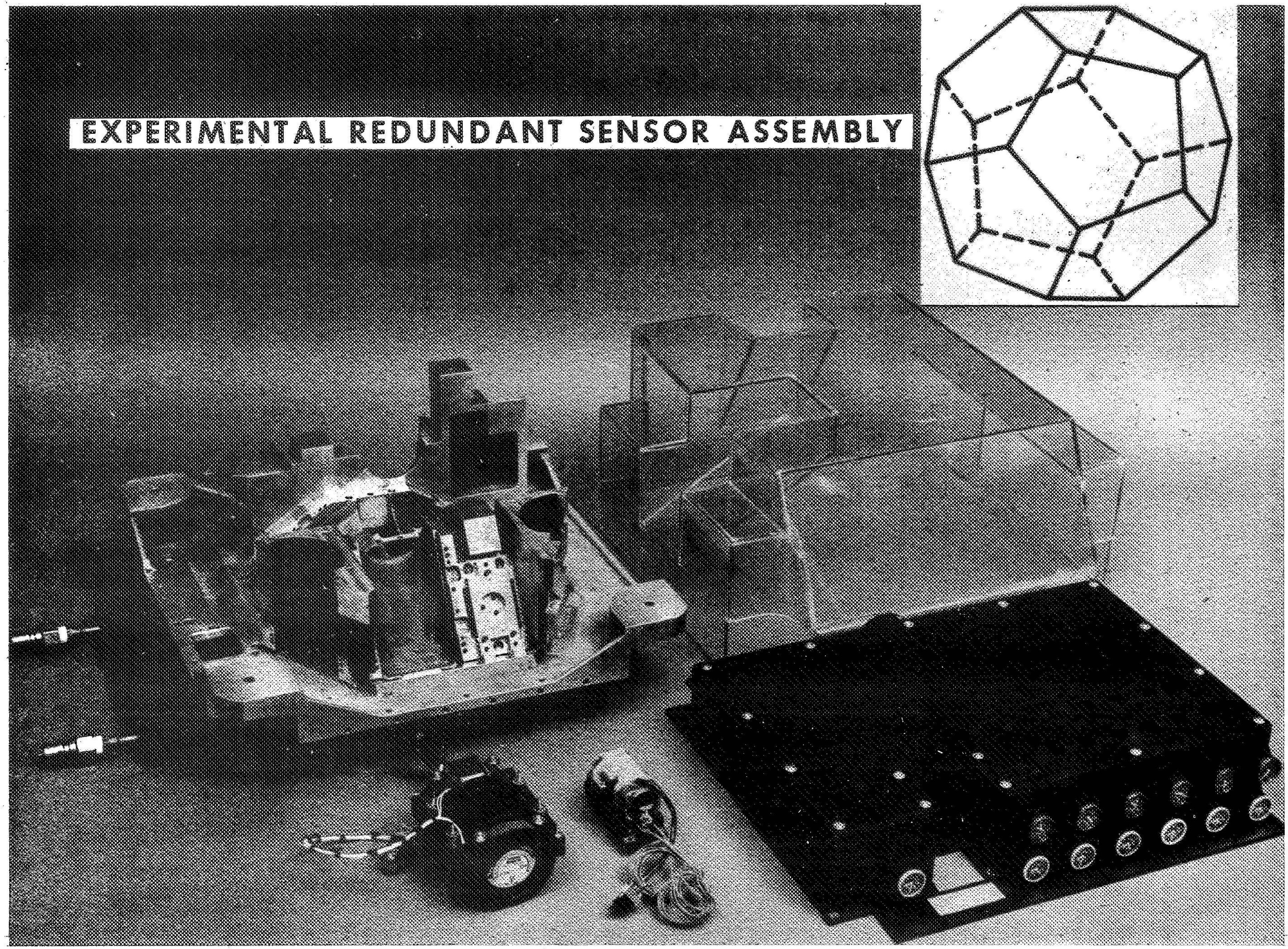


FIGURE VI The Experimental Redundant Sensor Assembly (ERSA) showing the platform, water cooled coldplate, and electronics subassembly. The line projection depicts the dodecahedron planes suitable for sensor mounting.

number of inertial components. Since redundancy contributes its greatest reward when there is a component failure, the potential of the system would be sensitive to degradation of performance of the remaining units due to perturbation of the temperature conditions of the IMU by the component malfunction. Thus one of the objectives of the ERSA program was to verify the magnitude of temperature perturbations resulting from various modes of gyro failures. In addition, other features of the redundant system including software development were also to be studied.

Design Requirements

Operating temperatures.--The ERSA system was designed to operate in environment temperatures from $30^{O}F$ to $120^{O}F$.

Test plan.--Outline a test plan for verification of the thermal design of the ERSA.

System Design

The ERSA IMU was also designed around an aluminum casting for the block. The inertial components were to be mounted on surfaces corresponding to the principal faces of a projected dodecahedron. The thermal control system consisted of twelve individual control loops, plus a block loop, plus an air-cooled cold plate.

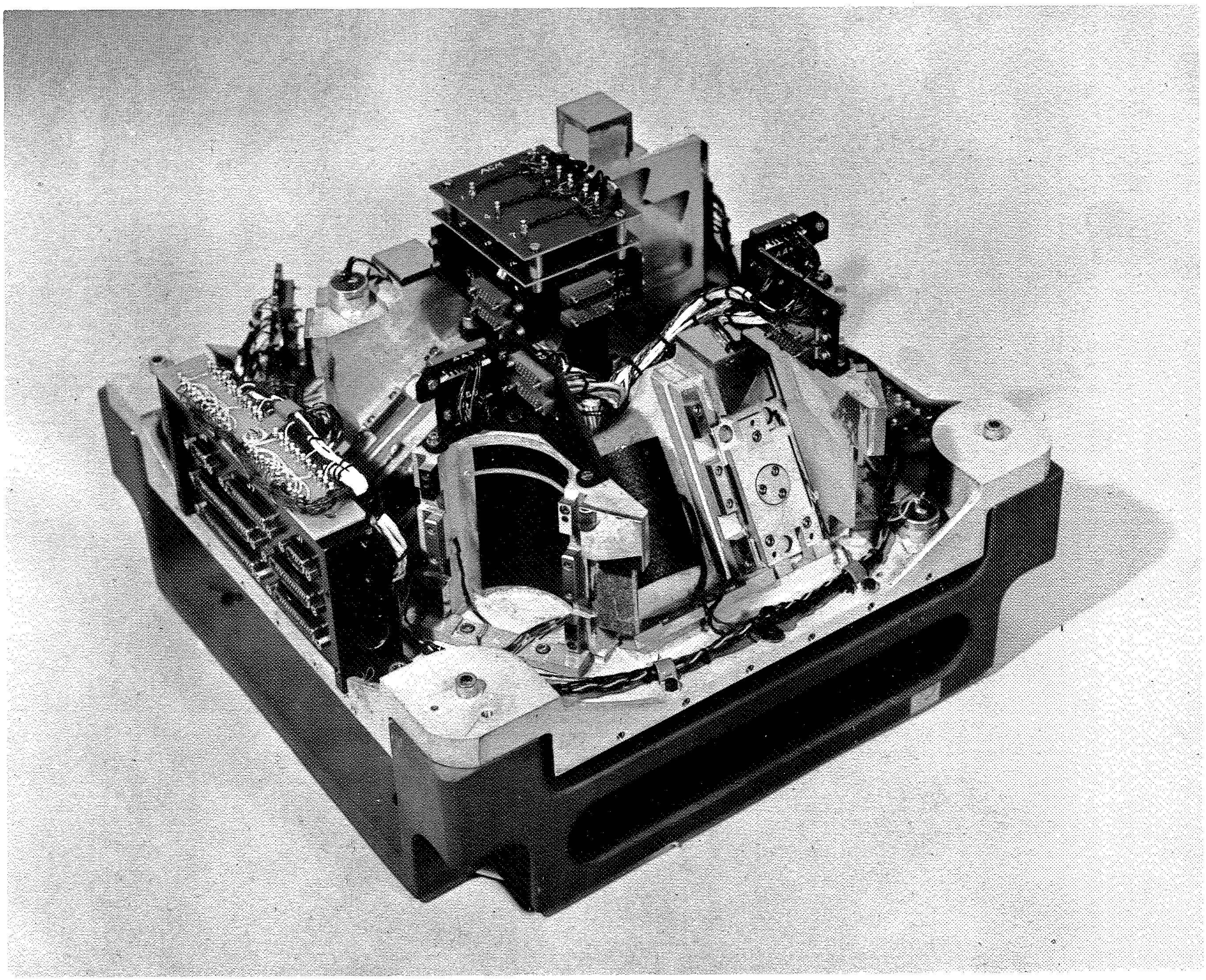
The inertial components were located in pre-aligned adapters to minimize thermal gradients around the components.

The system was modeled and various aspects of performance were examined using a computer program to simulate various operating modes.

System Performance

The overall thermal performance of the ERSA system was evaluated for a number of flight conditions. The resulting temperature profiles indicated that with the block loop and the component loops operating the inertial components could easily be controlled to the desired level of temperature for an invironment temperature variation from $30^{O}F$ to $120^{O}F$.

The principal component failure modes studies was the case of a complete loss of gyro power, and the case of large



VII ERSA assembly including heaters and thermal mounting pads.

dissipation of power at one of the gyros. For the first case, the thermal control systems were able, under all possible conditions, to compensate and maintain control at each of the remaining components. For the second case, only extreme conditions equivalent to dissipations greater than twice nominal for any failed component produced operating temperatures at the other components which exceeded acceptable values.

Test plan.--A preliminary test plan for evaluation of the thermal performance of the ERSA/IMU was recommended. This plan included a study of the variations in critical temperatures as well as a suggestion that the change in overall performance be determined for conditions of component failure. This plan is shown in Appendix M.

APPENDIX A

Material Properties

ROOM-TEMPERATURE PROPERTIES OF VARIOUS MATERIALS

Material	Thermal Conductivity, Btu-ft/hr-ft^2-^{o}F	Thermal Exp. Coeff. Near R.T., in/in/^{o}F	Heat Capacity Btu/lb/^{o}F
A356Al	90	11.5	0.23
2024-T4Al	70	12.5	0.20
6061-T6Al	96	13.0	0.23
Be	104	6.4	0.445
TZM-Mo	81	2.9	0.065
BeO	152	3.1	0.25
Al_2O_3	1.45	3.9	0.19
Precedent 71	30	13.7	.23

ROOM-TEMPERATURE PROPERTIES OF VARIOUS MATERIALS

Material	Density, g/cc	Young's Modulus, 10^6 psi	MYS Range Expected, 10^3 psi
A356Al	2.68	10	6-12
2024-T4Al	2.77	10	20-40
6061-T6Al	2.70	10	10-25
Be	1.85	44	2-40
TZM-Mo	9.10	43	25-60
BeO	3.0	52	20(a)
Al_2O_3	3.98	56	23(a)
Precedent 71	2.60	10.3	10

(a) These are fracture strengths, in tension.

APPENDIX B

Comparison of Thermal Control Modes

Some of the relative merits of the various possible modes of thermal control can be determined in terms of the thermal resistance and the number and location of the thermal control loops used. In its simplest form the principal thermal resistances of the IMU can be represented by the configuration of

The use of individual control loops at each sensor will be compared with the use of a block control loop. This comparison will be limited to an analysis of the difference in thermal control power and quiescent power requirements of the two modes. The principal parameters influencing the performance will be the number of loops utilized and the efficiency and location of the loops. A more complete evaluation would additionally include a comparison of the total weight and volume associated with each mode.

If individual control loops are located at each sensor, then for a three asis system,

$$Q_g R_g + 3(Q_g + Q_a) R_L = \Delta T \qquad (1)$$

and

$$Q_a R_a + 3(Q_a + Q_g) R_L = \Delta T \qquad (2)$$

where

$$Q_g = Q' \text{ (gyro)} + Q \text{ (thermal control at the gyro)}$$

$$= Q'_g + Q_{gc} \qquad (3)$$

and equivalently for the accelerometer

$$Q_a = Q'_a + Q_{ac} \qquad (4)$$

But

$$Q_{gc} = q_{og}\ \eta_g \qquad (5)$$

and

$$Q_{ac} = q_{oa}\ \eta_a \qquad (6)$$

where the q is the true power consumed and η is the efficiency at which consumed power is converted to control power.

The total consumed power required to maintain the desired ΔT is

$$Q_{oT} = 3\ q_{oa} + 3\ q_{og} \tag{7}$$

where q_{oa} and g_{og} must be obtained from the solution of equations (1) to (6) above.

The true value of η_g is usually a function of the value of g_{og}, or equivalently Q_{cg}.

$$\eta_g = \frac{Q_{cg}}{q_s + \frac{Q_{cg}}{\bar{\eta}}} \tag{8}$$

where g_s is the minimum (zero output) "standby" power for the electronics of the thermal control loop and $\bar{\eta}$ is the conversion efficiency based on the incremental power input above the minimum value.

For given values of efficiency, thermal resistance, accelerometer power, gyro power, etc., the total control power requirement Q_{oT} can be obtained.

If a single loop block control is used the pertinent equations are

$$Q'_a R_a + 3(Q'_g + Q'_c)\ R_L + Q_{Bc} R_L = \Delta T \tag{9}$$

$$Q'_g R_g + 3(Q'_g + Q'_c)\ R_L + Q_{Bc} R_L = \Delta T \tag{10}$$

and

$$Q_{oT} = Q_{Bc}/\eta \tag{11}$$

also

$$\eta = \frac{Q_{Bc}}{q_s + \frac{Q_{Bc}}{\bar{\eta}}} \tag{12}$$

Examination of the equations for individual loops shows that, ideally, if individual controllers are used, correct selection of R_L would result in zero control power requirement if $Q'_a R_a = Q'_g R_g$. This same condition could also be maintained with block control. However, the standby power for individual control loops would be 6q where for block control this would only be q. This difference, however, is expected to be only of the order of 500 mw. Thus, it appears that weight and volume, or the power requirements as determined by a particular mission temperature variation would determine the preferred mode. In any case, the equations derived above can be used to analyze and compare the performance.

APPENDIX C

COMPARISON OF FIXED THERMAL RESISTANCE VERSUS A VARIABLE THERMAL RESISTANCE

In order to minimize the required thermal control power of a system which can encounter extremely different external temperatures it is advantageous to be able to vary the net thermal resistance of the system between the critical components and ambient. The magnitude of the power reduction can easily be determined.

Let

$$Q\ (\text{total}) = Q\ (\text{Sensors}) + Q\ (\text{Electronics on Block}) + Q\ (\text{Control})$$

or

$$Q_T = Q_o + Q_c$$

From the definition of the thermal resistance R,

$$Q_T = \frac{1}{2}\left(T_{sensor} - T_{ambient}\right)$$

$$= \frac{1}{2}\,\Delta T$$

If R is fixed at R_F the minimum control power can be determined.

$$Q_{c,min} + Q_o = \frac{\Delta T(\text{min})}{R_F}$$

where R_F is usually chosen so that $Q_{c,min}$ is approximately zero.

At $\Delta T(\text{max})$

$$Q_o + Q_{c,min} + Q_c{}' = \frac{\Delta T(\text{max})}{R_F}$$

$$Q_c{}' = \frac{\Delta T(\text{max})}{R_F} - \left(Q_o + Q_{c,min}\right)$$

or

$$Q_c' = \frac{\Delta T(\max) - \Delta T(\min)}{R_F}$$

and thus, for a fixed thermal resistance

$$\frac{Q_c'}{Q_o + Q_{c,min}} = \frac{\Delta T(\max) - \Delta T(\min)}{\Delta T(\min)}$$

For the total possible range of external temperatures of 30^oF to 120^oF, and for sensor temperatures of 150^oF

$$\frac{Q_c'}{Q_c + Q_{c,min}} = \frac{(150-30) - (150-120)}{(150-120)} = 3.0$$

If however, R can be varied as ΔT varies, then $\frac{\Delta T}{R}$ can be held constant and Q_c can always be held essentially equal to $Q_{c,min}$, with a net power savings equalt to Q_c' calculated above.

APPENDIX D

Free Vibration Analysis of NASA Laser Gyro IMU

The Laser Gyro IMU, including the sensors, was first modeled as a discrete mass system by distributing the mass of the package and sensors into sixty points. This model simulated the elastic structure by connecting the mass points with 84 triangular elastic plates and 41 elastic bars.

A free vibration analysis of this modal was made using STARDYNE, a finite element digital computer program. The program computed the equivalent stiffness matrix for the model and extracted the two lowest natural frequencies and corresponding modal shapes for the structural model. The mode corresponding to the lowest frequency, 247 Hz, is indicated in the accompanying figures.

Considering the coarseness of the discrete model, especially in the vicinity of the holes in the structure, one would expect that 247 Hz is a slight over-estimation of the correct lowest natural frequency since with only 60 nodal points, the model is more constrained than the actual structure.

In this discrete mass models of the Laser Gyro IMU, the gyros are mounted on the sides of the structure designated as left, back, and top. The heat exchanger is mounted on the bottom, while the rectangular opening at the front represents the location of the access door.

The origin of coordinates for the reference axes is located at the bottom left hand corner of the front face. With respect to this origin, X_1 is measured upward, X_2 toward the right, and X_3 toward the back.

Figures D1 through D6 represent the mode shape corresponding to the lowest natural frequency of this model. The numbers in the figures designate the locations of the nodes. In this model, each node is a concentrated mass. Nodes 1, 2, and 3 represent the supports for the structure which are held fixed. The displacements have been normalized with respect to a unit displacement of node 58 in the direction of X_1 axis.

The effect of the laser gyro dither on the support structure was considered by inputing time dependent forces at the gyro mounts. A new model of the structure was created for this study. This model did not include the gyro masses and was less stiff than the first model thus providing a conservative estimate of the dither effects. The first resonant frequency for this model was 206Hz.

Figures D7 through D12 show the distribution of nodes for this structure. It differs from the first model in that not all the nodes represent masses. In this way, the structure could be modeled more accurately without a significant increase in computer time. Also, the nodal numbering for this structure is not the same as that of the first model.

Figures D13 through D18 represent typical displacement response curves for the support structure subjected to in phase sinusoidal loads applied at the gyro supports. The displacements of these points were the largest in magnitude in their respective directions for the mode corresponding to the lowest natural frequency of the support structure.

The peaks in each curve correspond to that first three resonant frequencies 206 Hz, 444 Hz, and 498 Hz in the input range of 1Hz through 500 Hz. The response at the dither frequency, 113 Hz, can be compared to the essentially static level at 1 Hz.

Displacement and acceleration response were determined for each of the nodes over the input frequency range. These results available from either the contractor or technical monitor.

Mode Shape - Front

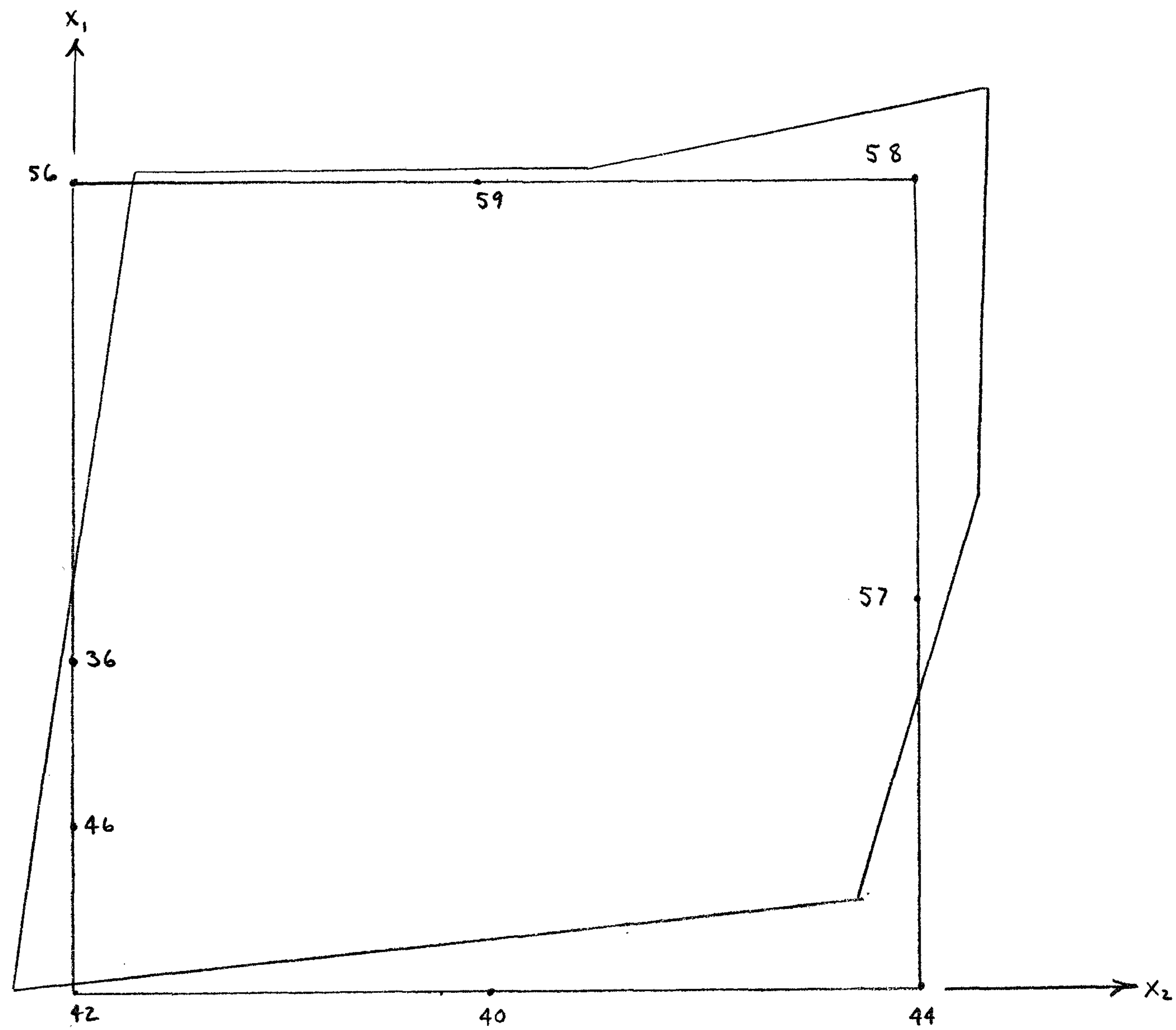


Figure D1

Mode Shape -Right Side

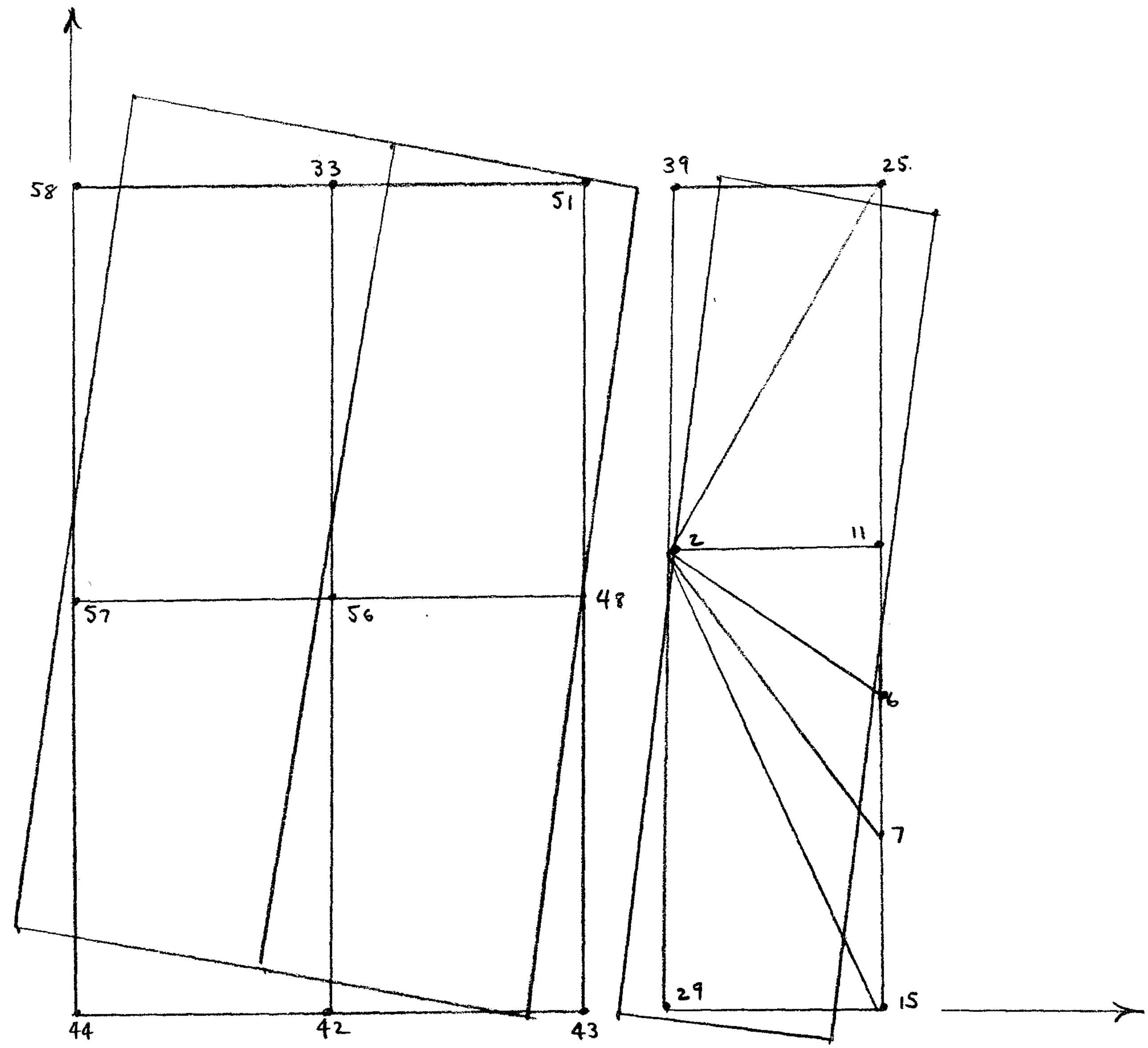


Figure D2

Mode Shape - Left Side

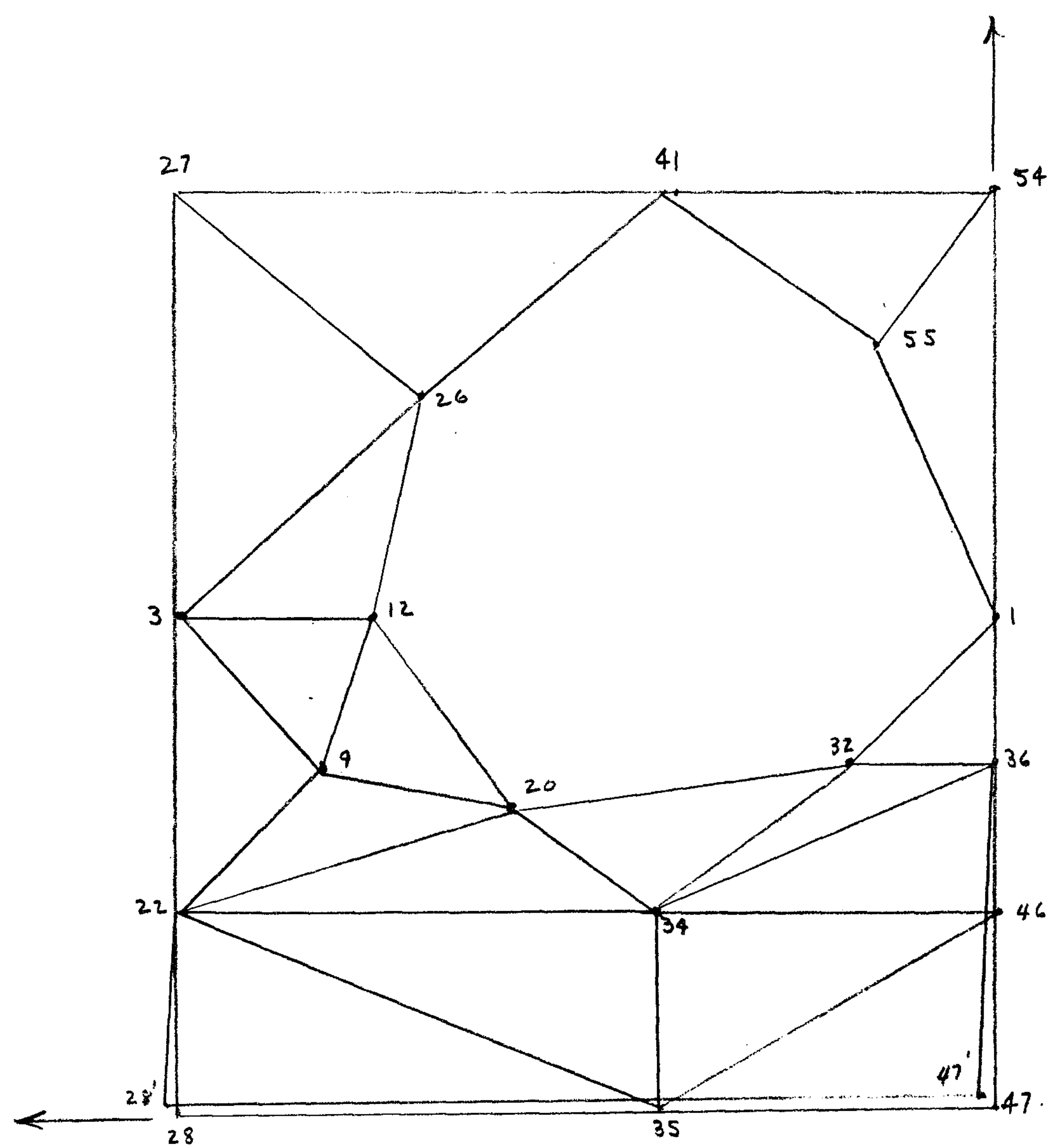


Figure D3

Mode Shape - Bottom

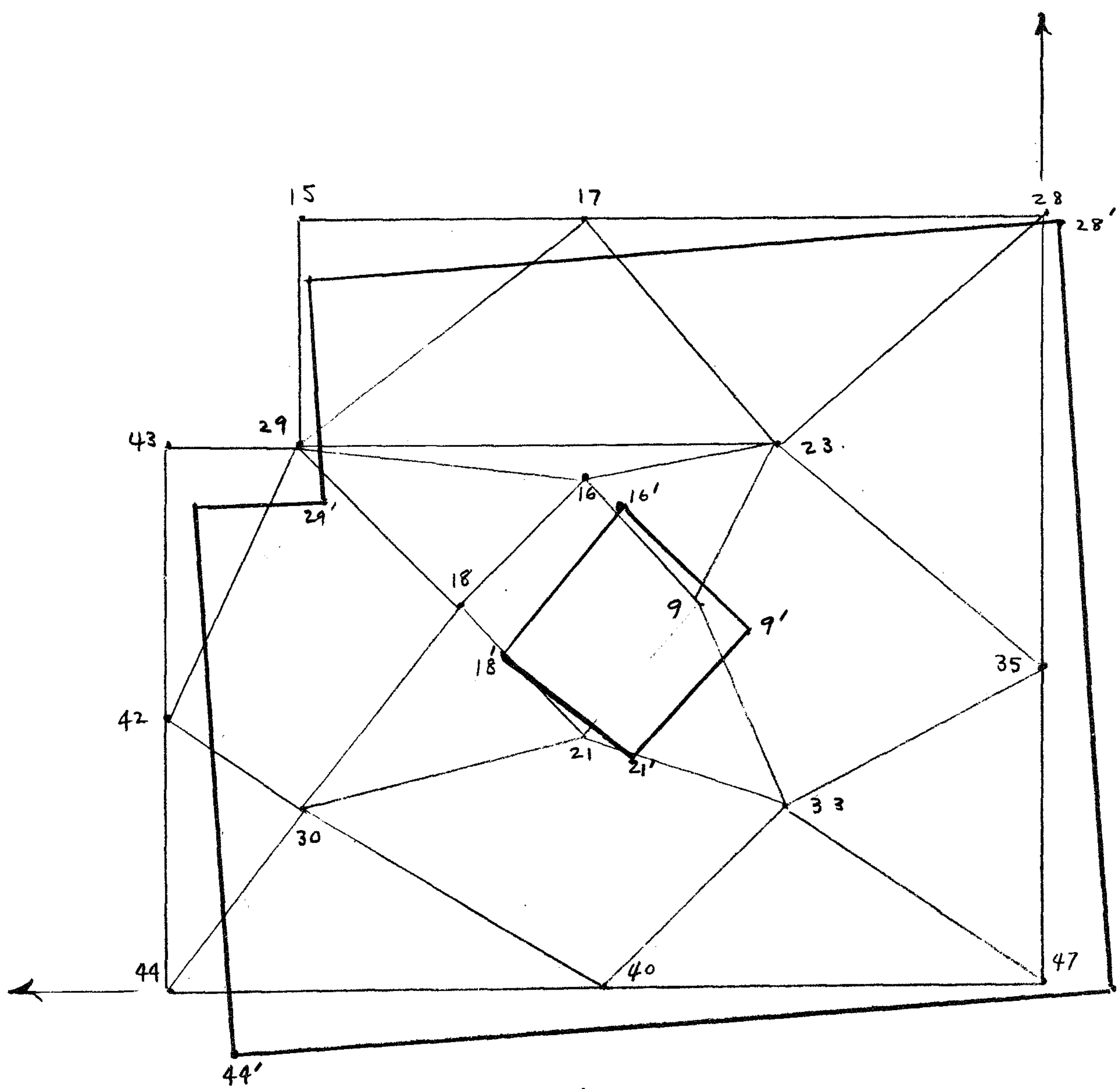


Figure D4

Mode Shape - Top

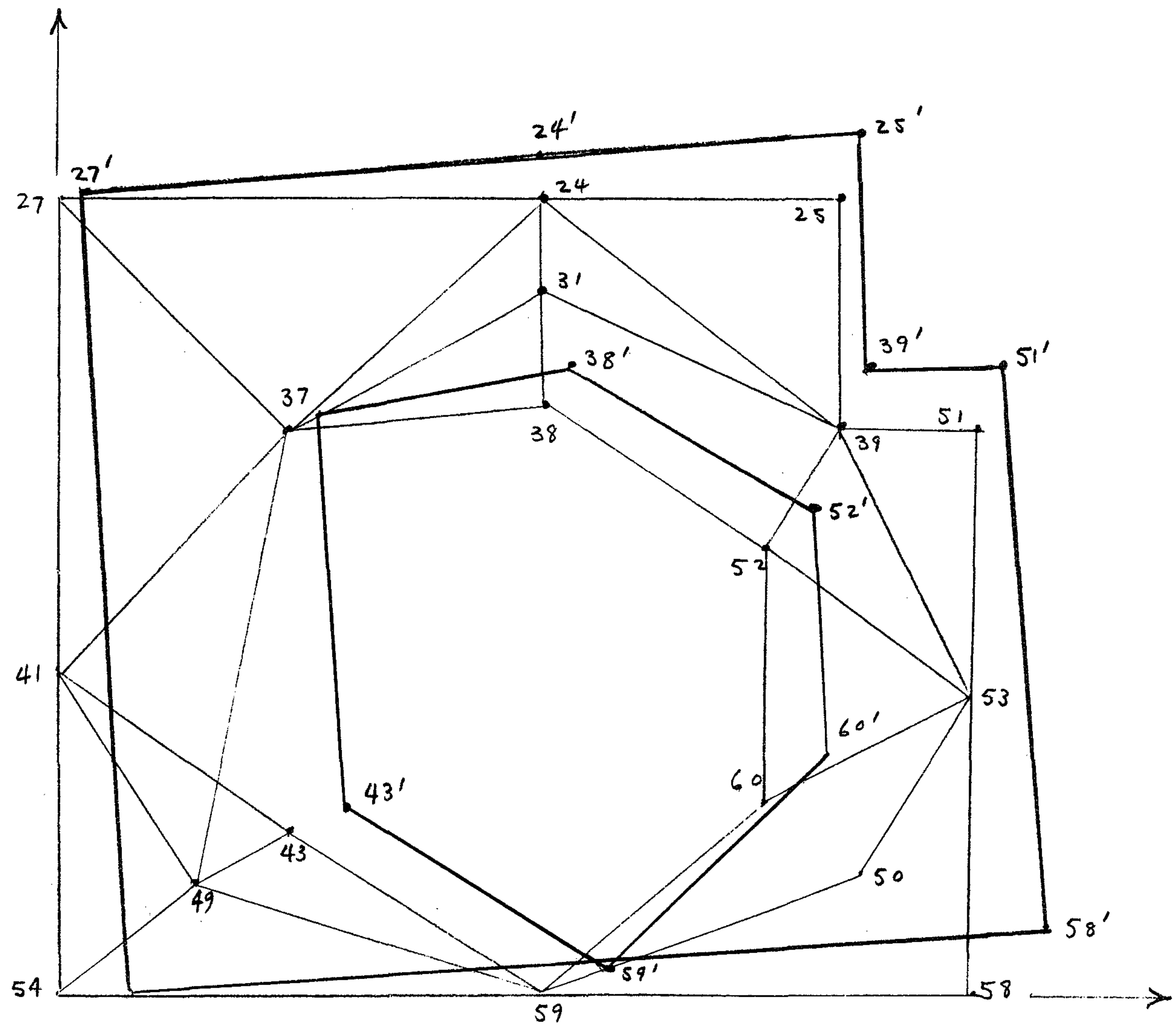


Figure D5

Mode Shape - Back

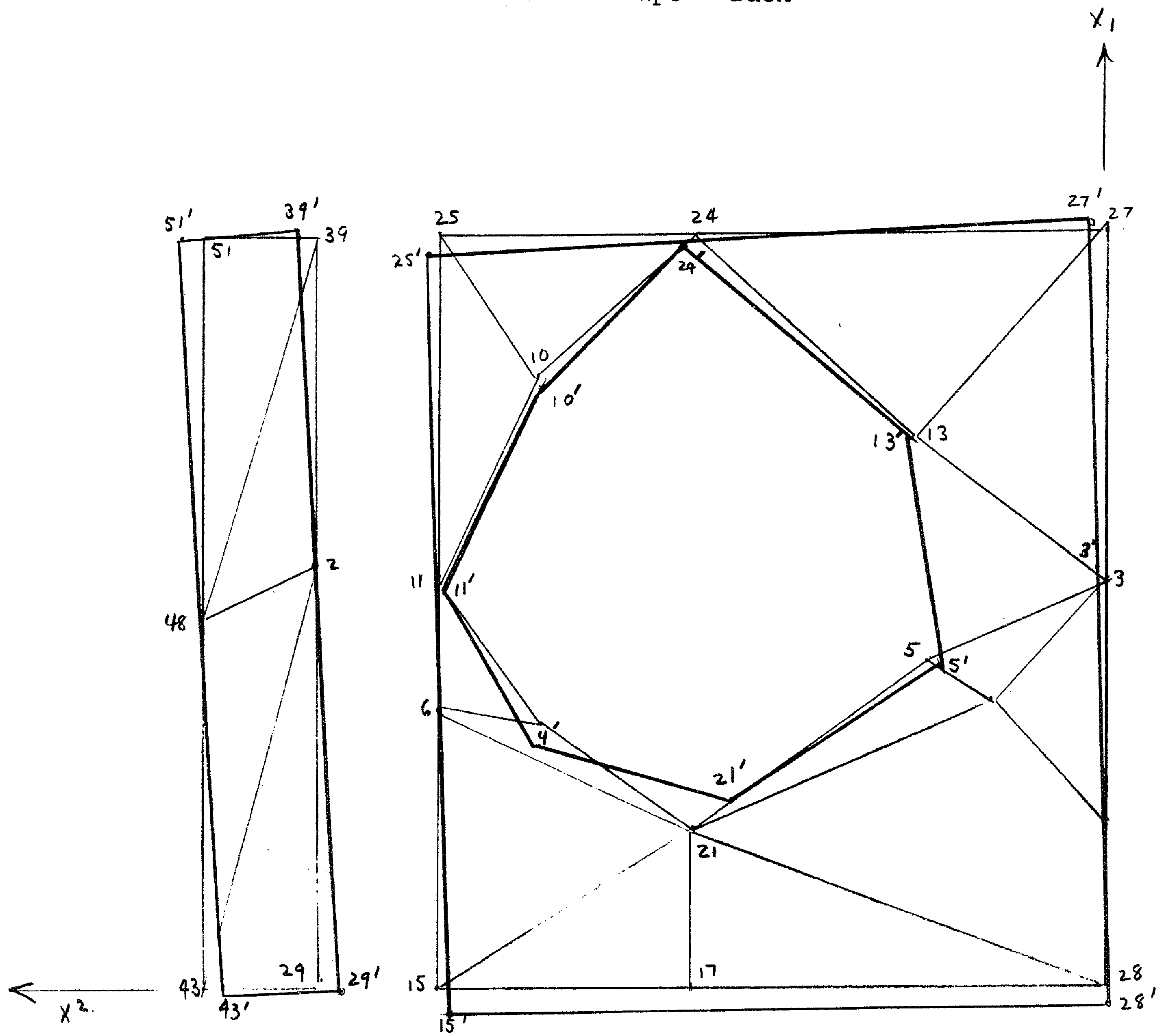


Figure D6

Nodal Distribution - Top and Bottom

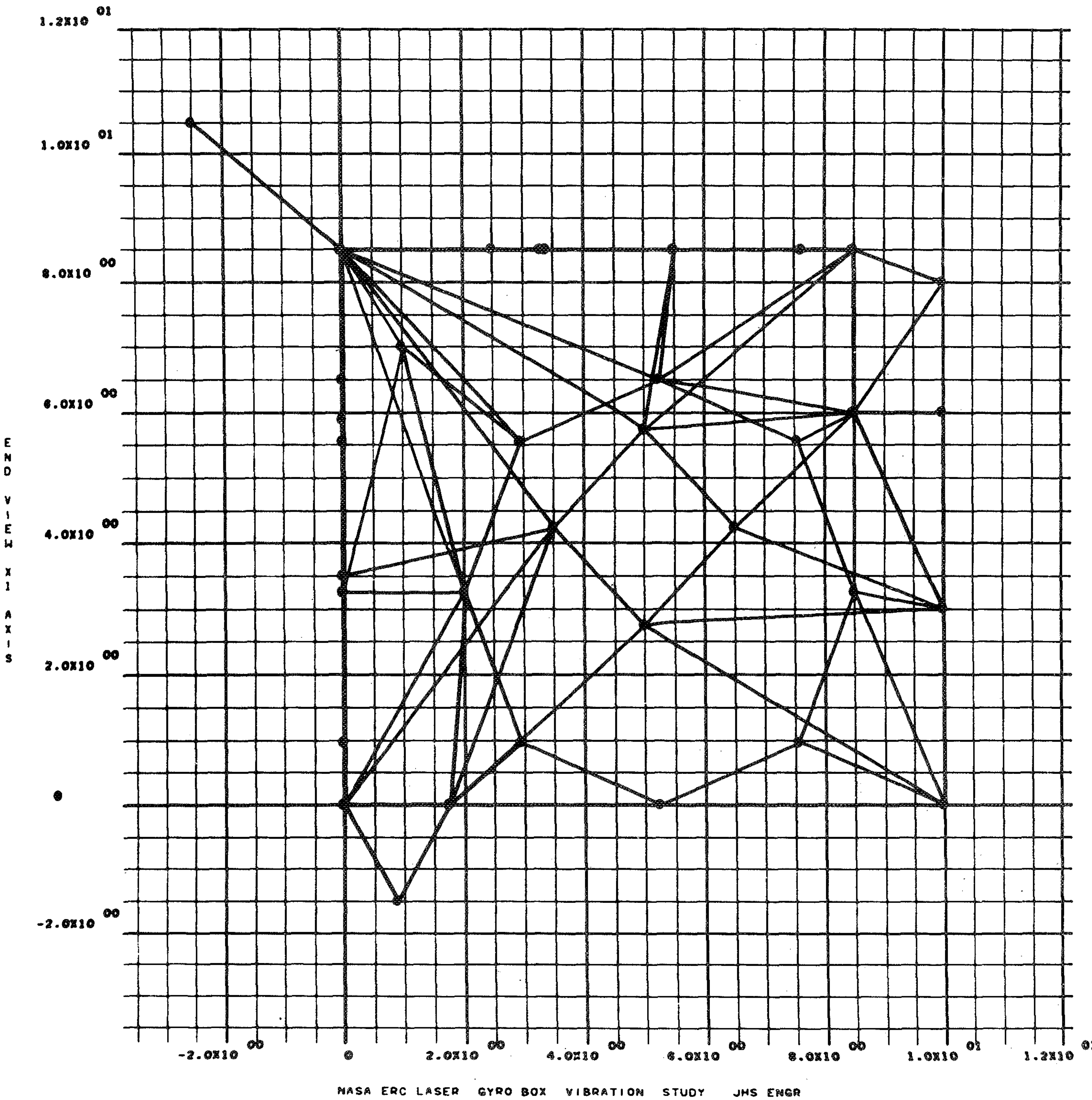


Figure D7

Nodal Distribution - Left and Right Sides

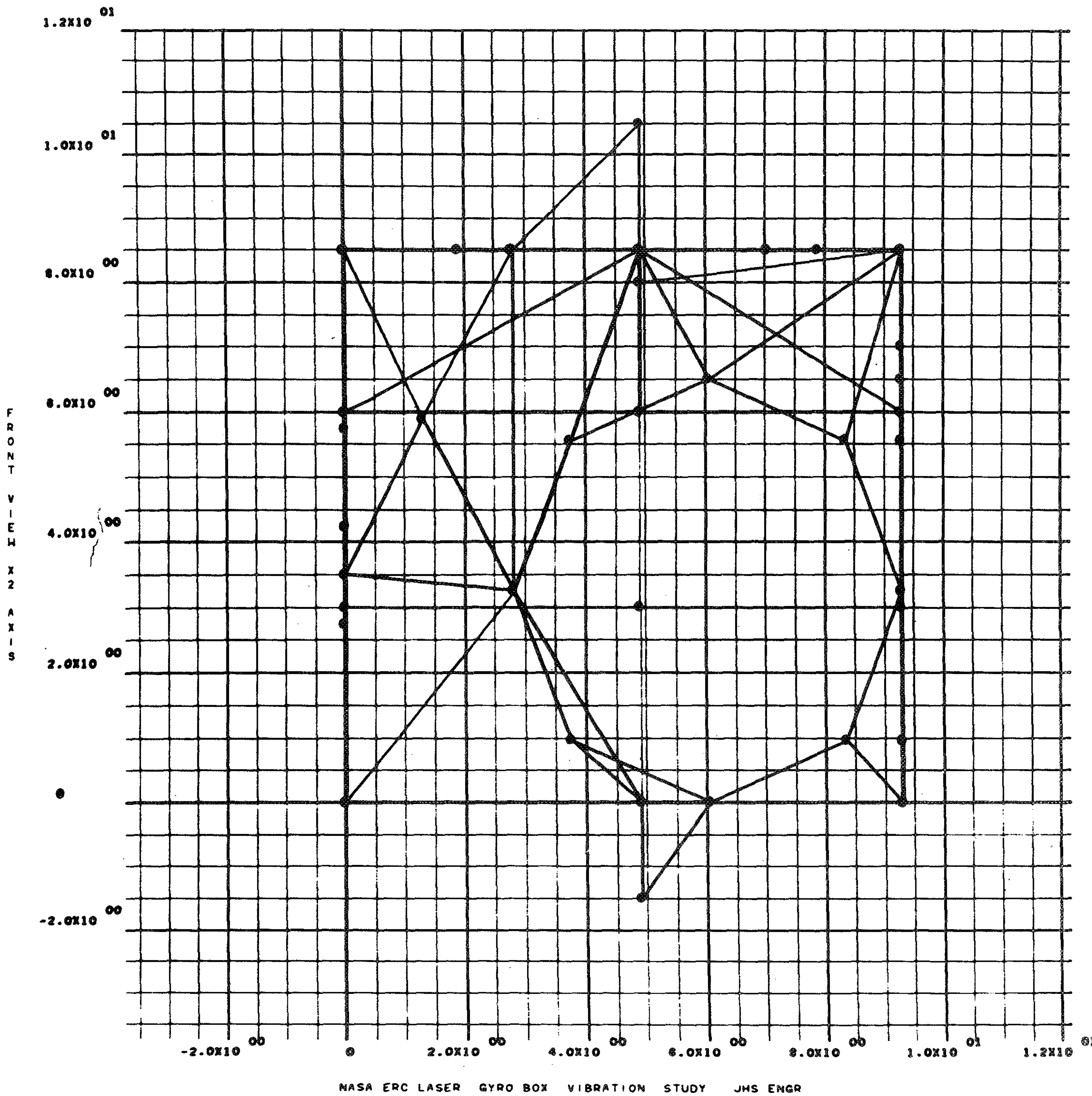


FIGURE D8

Nodal Distribution - Front and Back

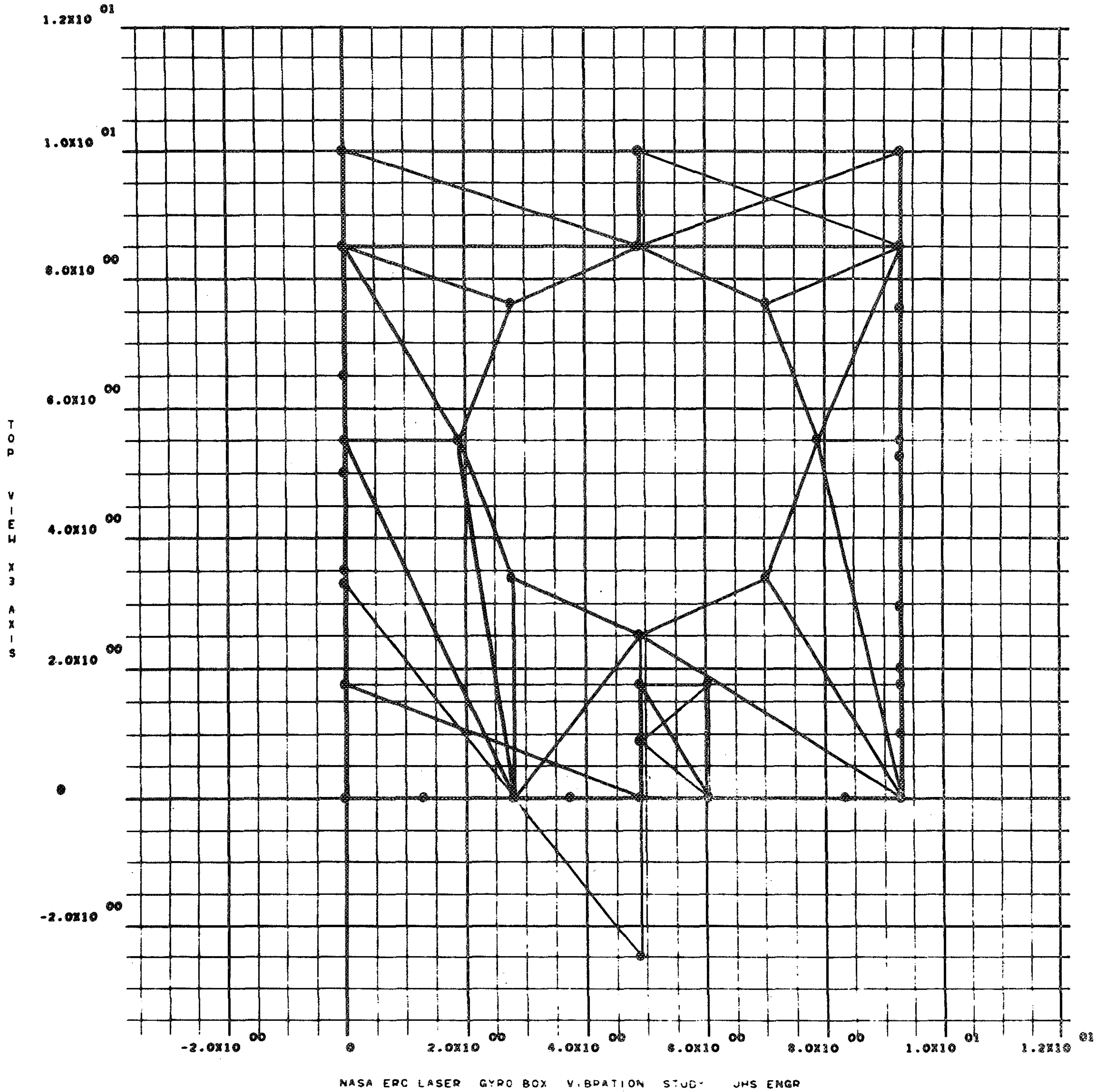


FIGURE D9

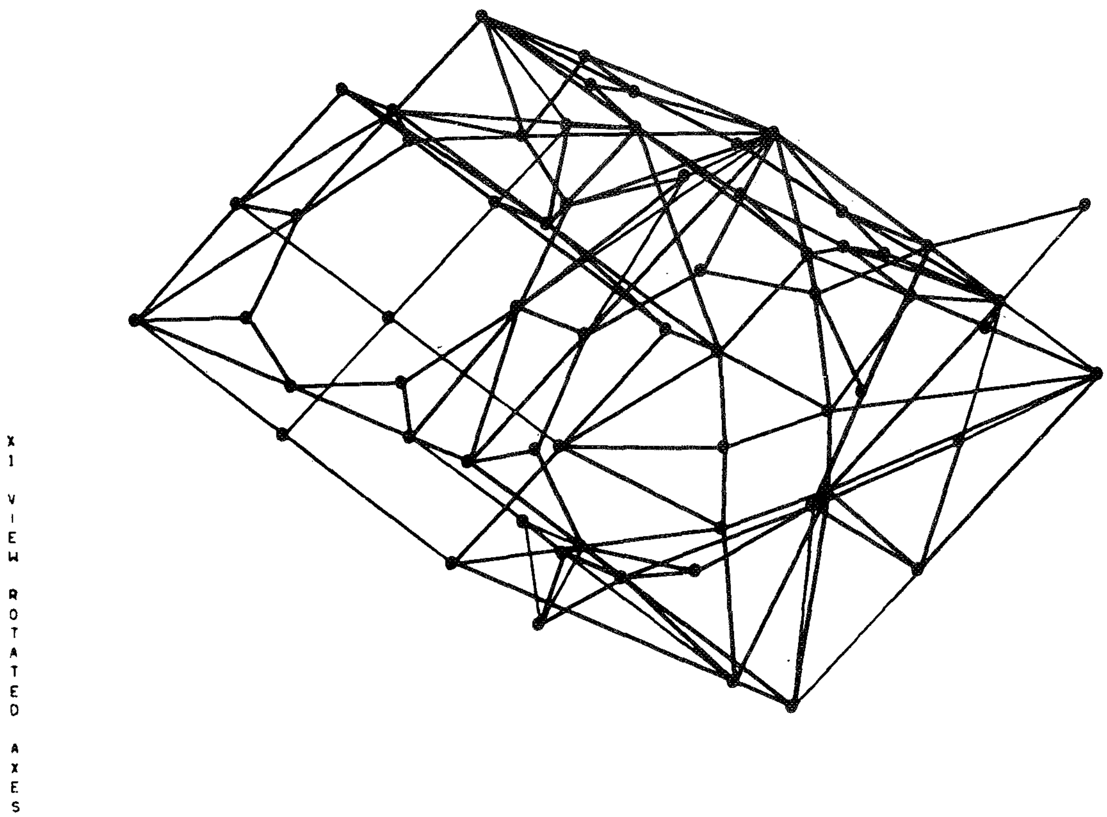
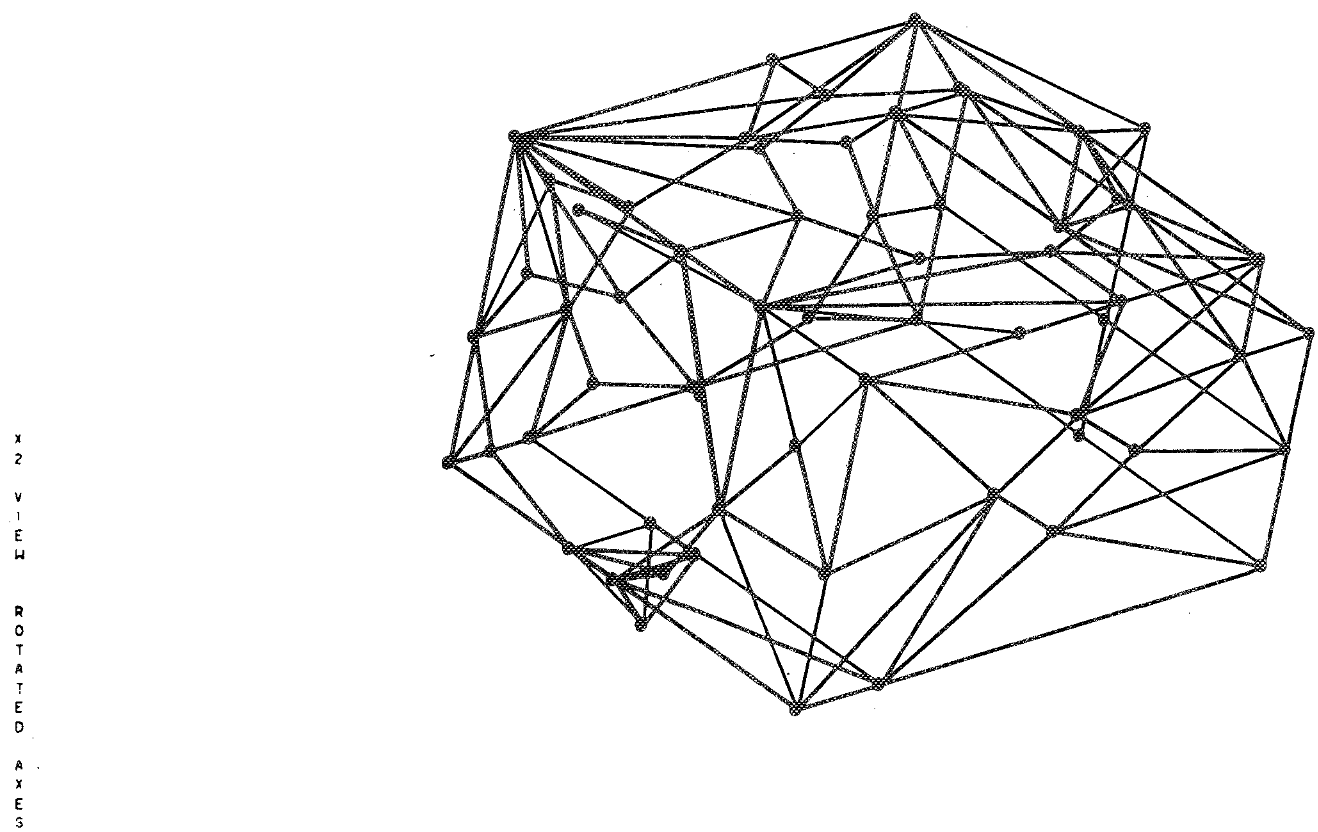

X1 VIEW ROTATED AXES
NASA ERC LASER GYRO BOX VIBRATION STUDY UHS ENGR

FIGURE D10



NASA ERC LASER GYRO BOX VIBRATION STUDY JHS ENGR

FIGURE D11

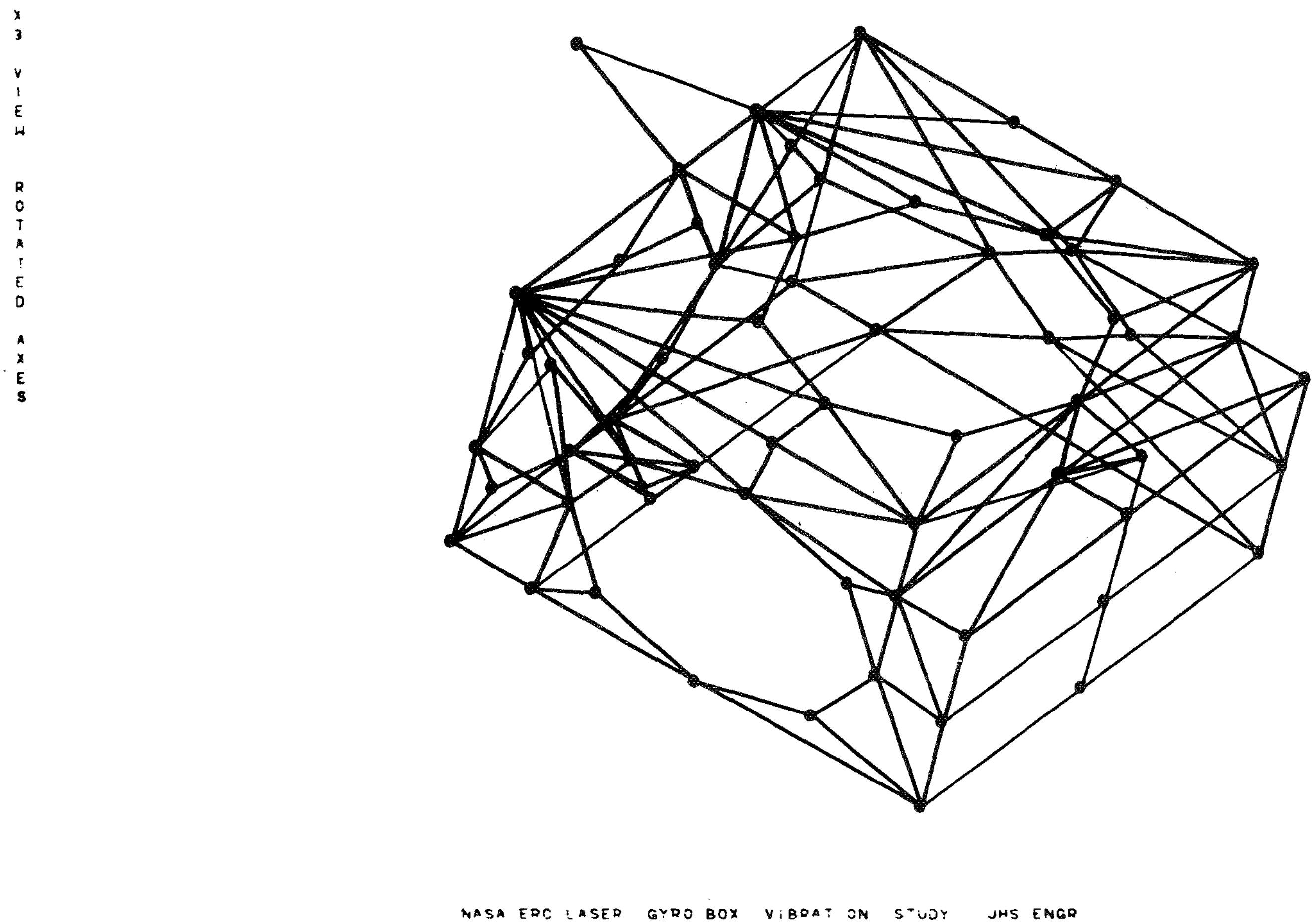

X3 VIEW ROTATED AXES
NASA ERC LASER GYRO BOX VIBRATION STUDY JHS ENGR

FIGURE D12

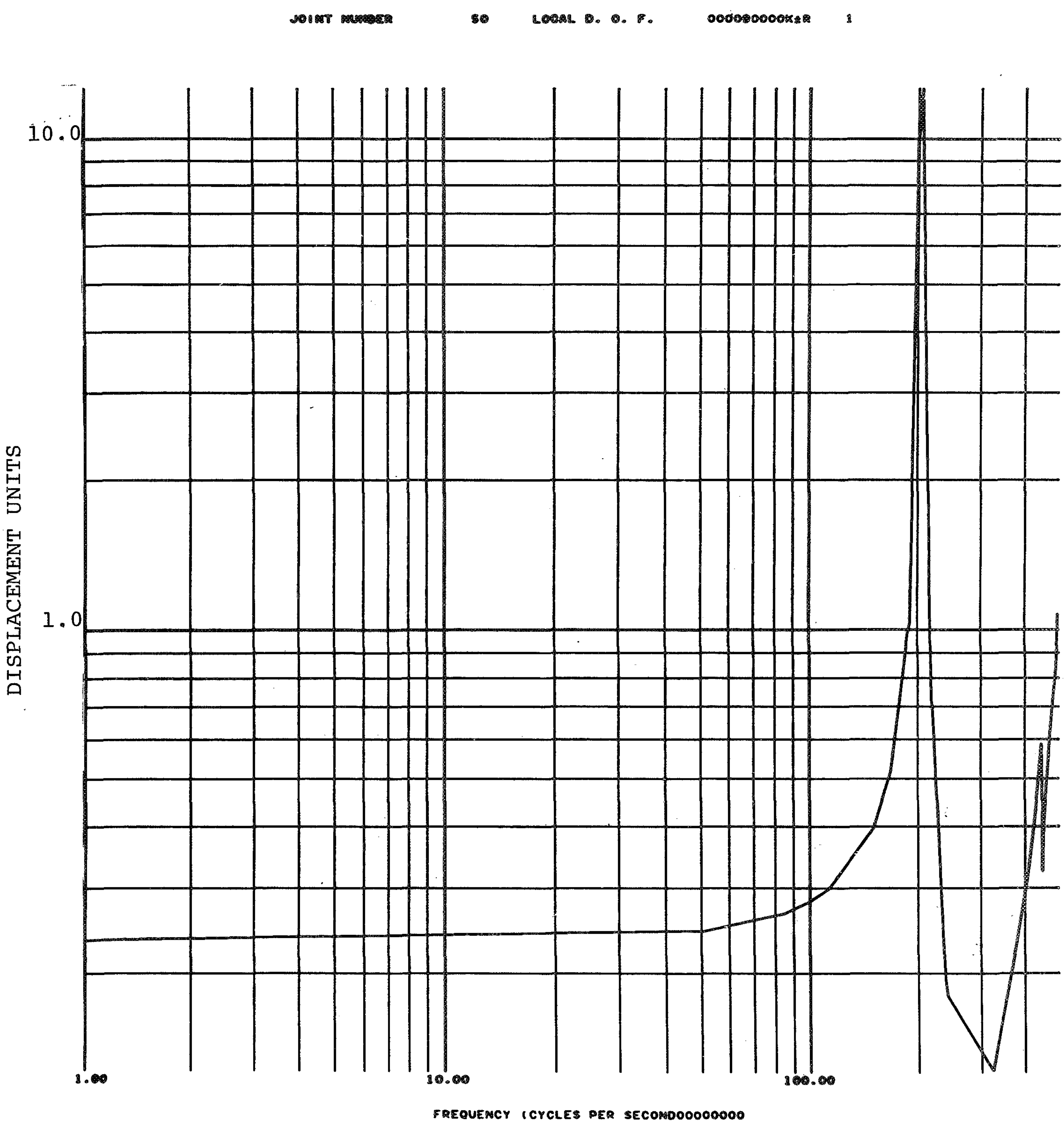

JOINT NUMBER 50 LOCAL D. O. F.
1
10.0
1.0
DISPLACEMENT UNITS
1.00
10.00
100.00
FREQUENCY (CYCLES PER SECOND00000000

Figure D13

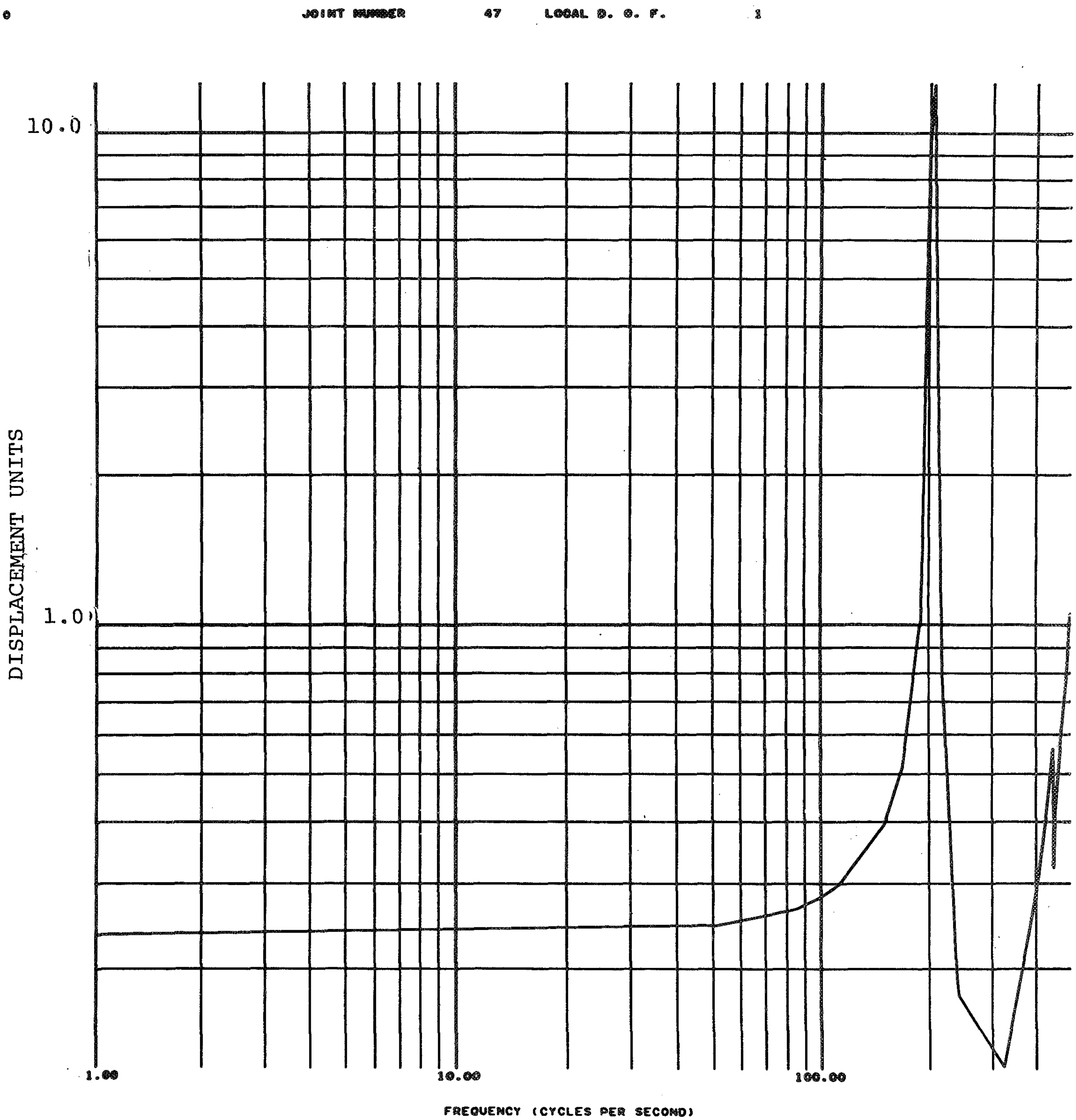
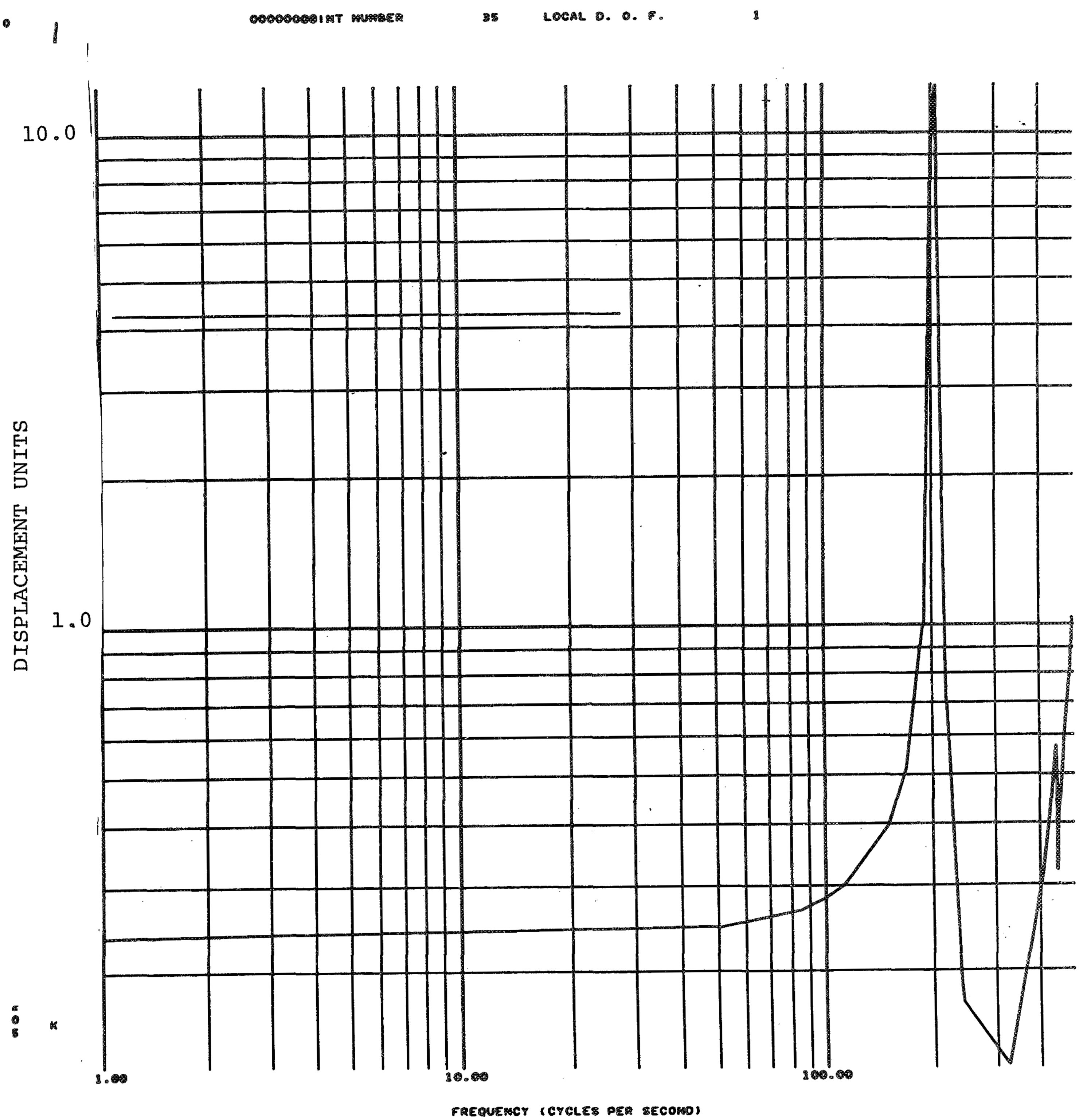

JOINT NUMBER 47 LOCAL D. O. F. 1
10.0
1.0
DISPLACEMENT UNITS
1.00
10.00
100.00
FREQUENCY (CYCLES PER SECOND)

Figure D14



OOOOOOOOBINT NUMBER 35 LOCAL D. O. F. 1
10.0
1.0
DISPLACEMENT UNITS
1.00
10.00
100.00
FREQUENCY (CYCLES PER SECOND)

Figure D15

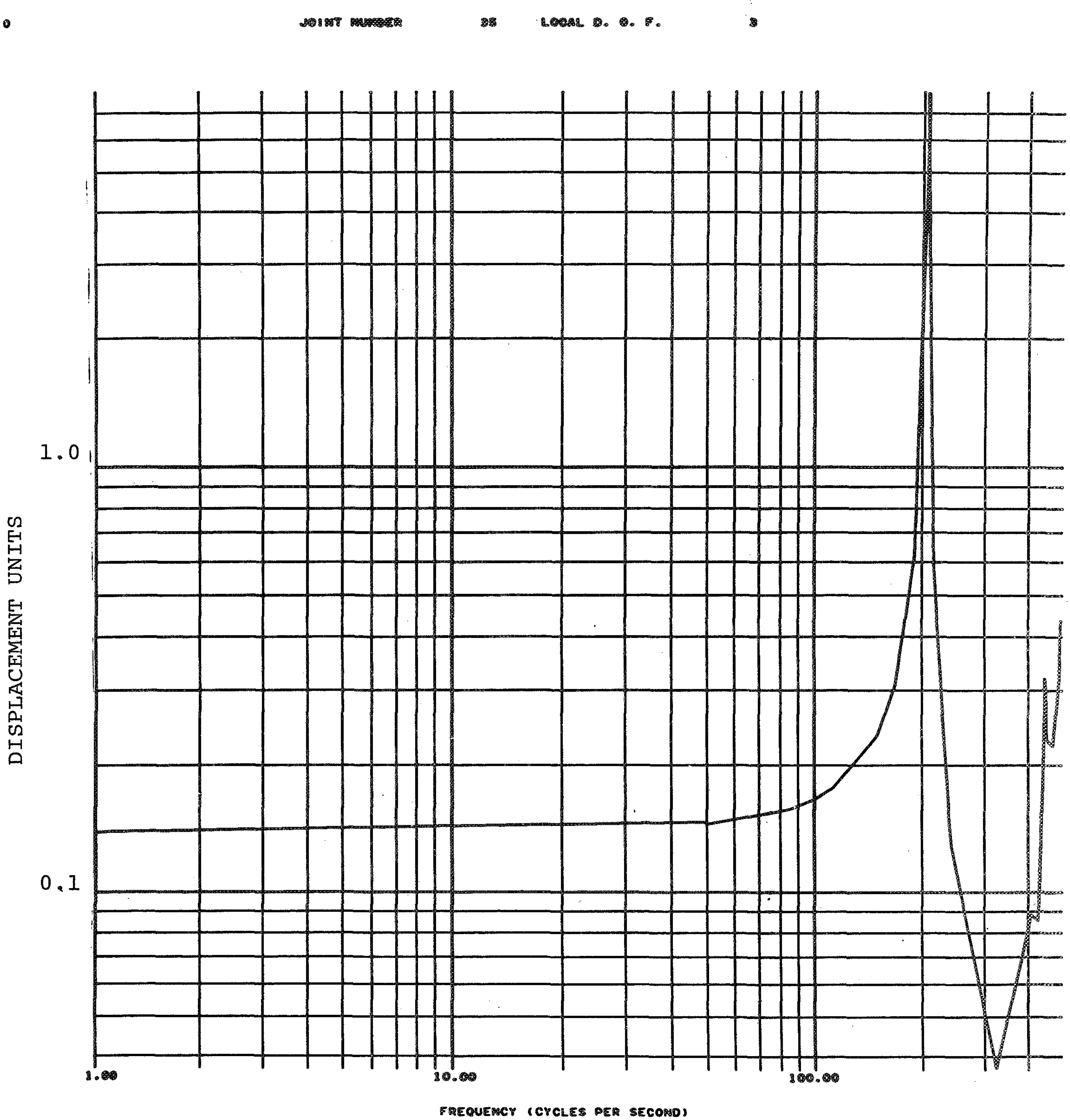

0
JOINT NUMBER 35 LOCAL D. O. F. 3
1.0
0.1
DISPLACEMENT UNITS
1.00
10.00
100.00
FREQUENCY (CYCLES PER SECOND)

Figure D16

0 JOINT NUMBER 36 LOCAL D. O. F. 3

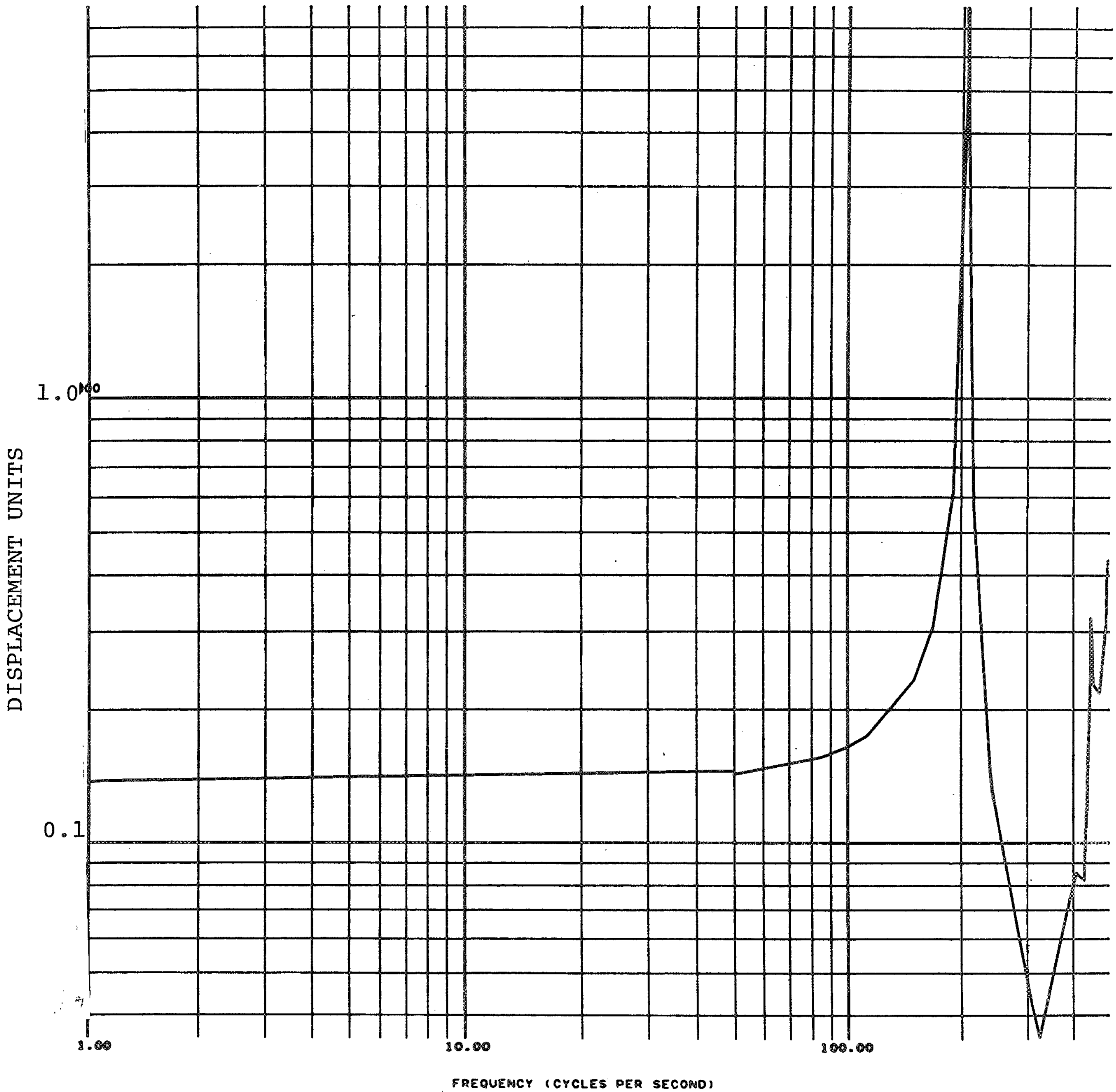
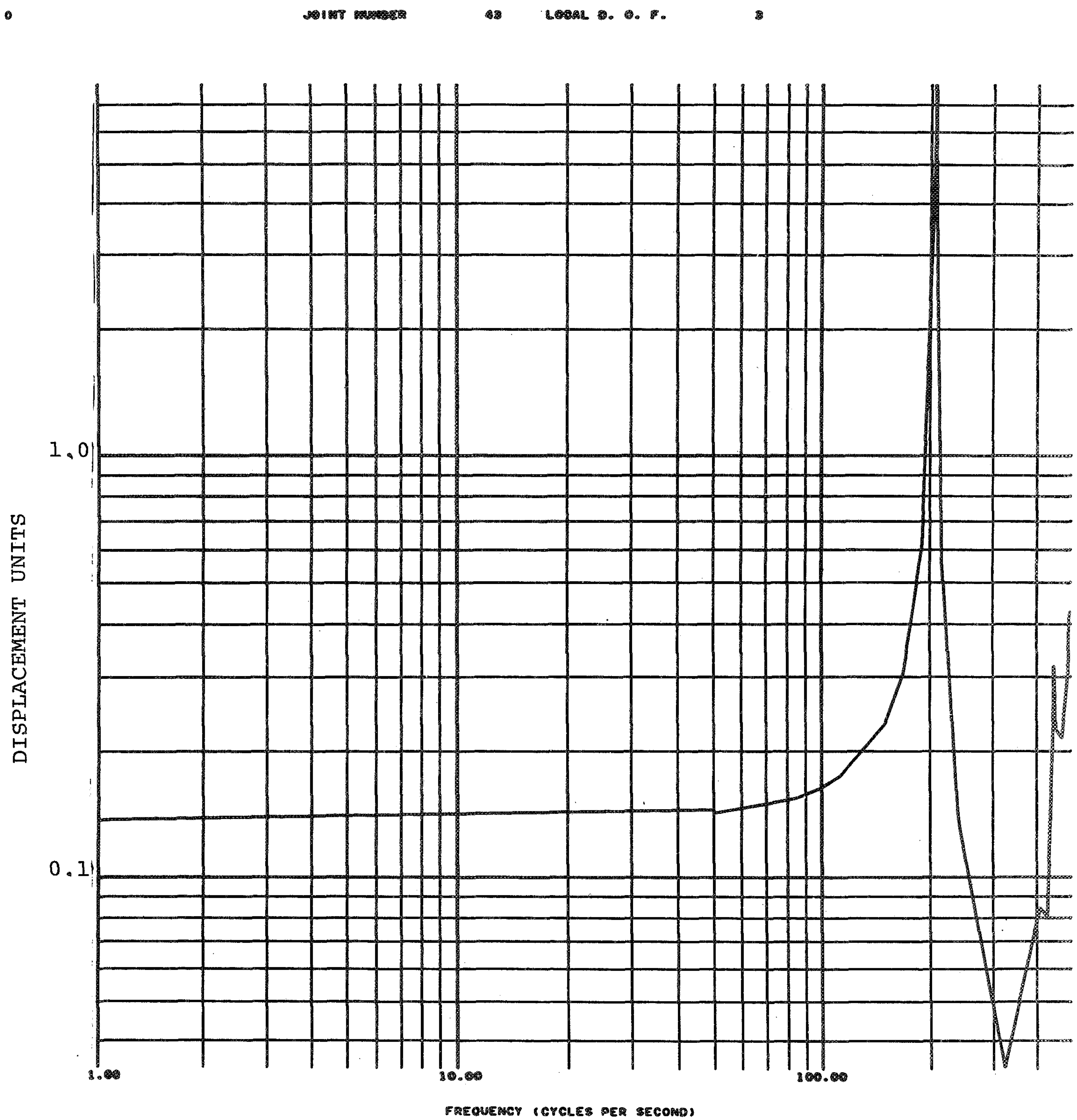


Figure D17

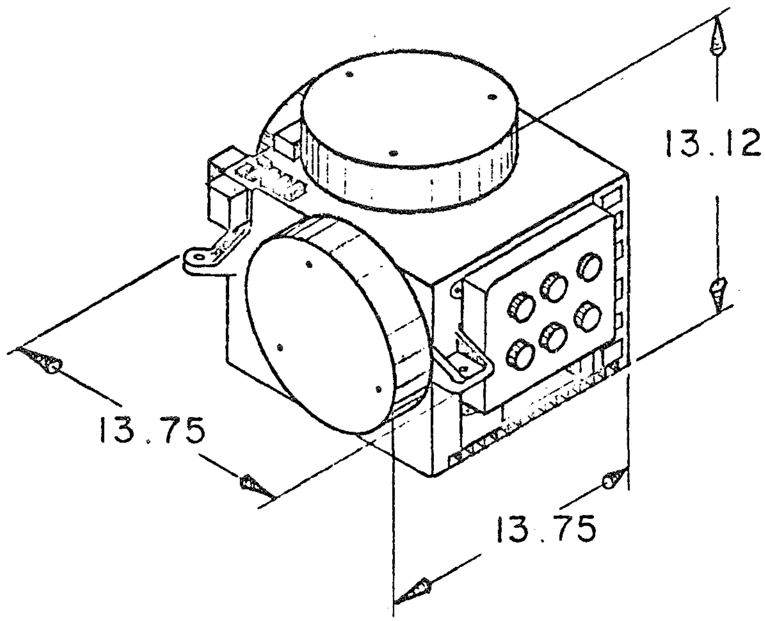


0
JOINT NUMBER 43 LOCAL D. O. F. 3
1.0
0.1
DISPLACEMENT UNITS
1.00
10.00
100.00
FREQUENCY (CYCLES PER SECOND)

Figure D18

APPENDIX E

Weight Budget for Laser IMU



IMU WT. — 86 LB (EXCLUSIVE OF INSULATED OUTER CASE)

% Percent Wt. Breakdown

INERTIAL COMPONETS	
a. GYRO	54.1
b. ACCEL	1.9
ELECTRONICS	13.4
INSULATION (INTERNAL)	1.7
STRUCTURE	15.1
HARDWARE (CABLING, BLOWER, DUCTING, MTG PLATES ETC.)	13.8
	100.0

APPENDIX F

Summary of Heat Treatment Procedures for Precedent 71A

T2 Condition: Stress relieved to give best possible dimensional stability, followed by a hardening treatment (aging) for free machinability.

(a) Hold at 775°F ± 25° for 5 hours.

(b) Cool from 775°F to 650°F in 2 or more hours.

(c) Cool from 650°F to 450°F in not more than one hour.

(d) Cool from 450°F to 250°F in approximately 2 hours.

(e) Cool from 250°F to room temperature in still air outside the furnace.

(f) Harden by reheating to 330°F from 6 to 16 hours and cooling outside the furnace in still air. (Time required depends on variations in cooling rate between 650°F-450°F after stress relief.)

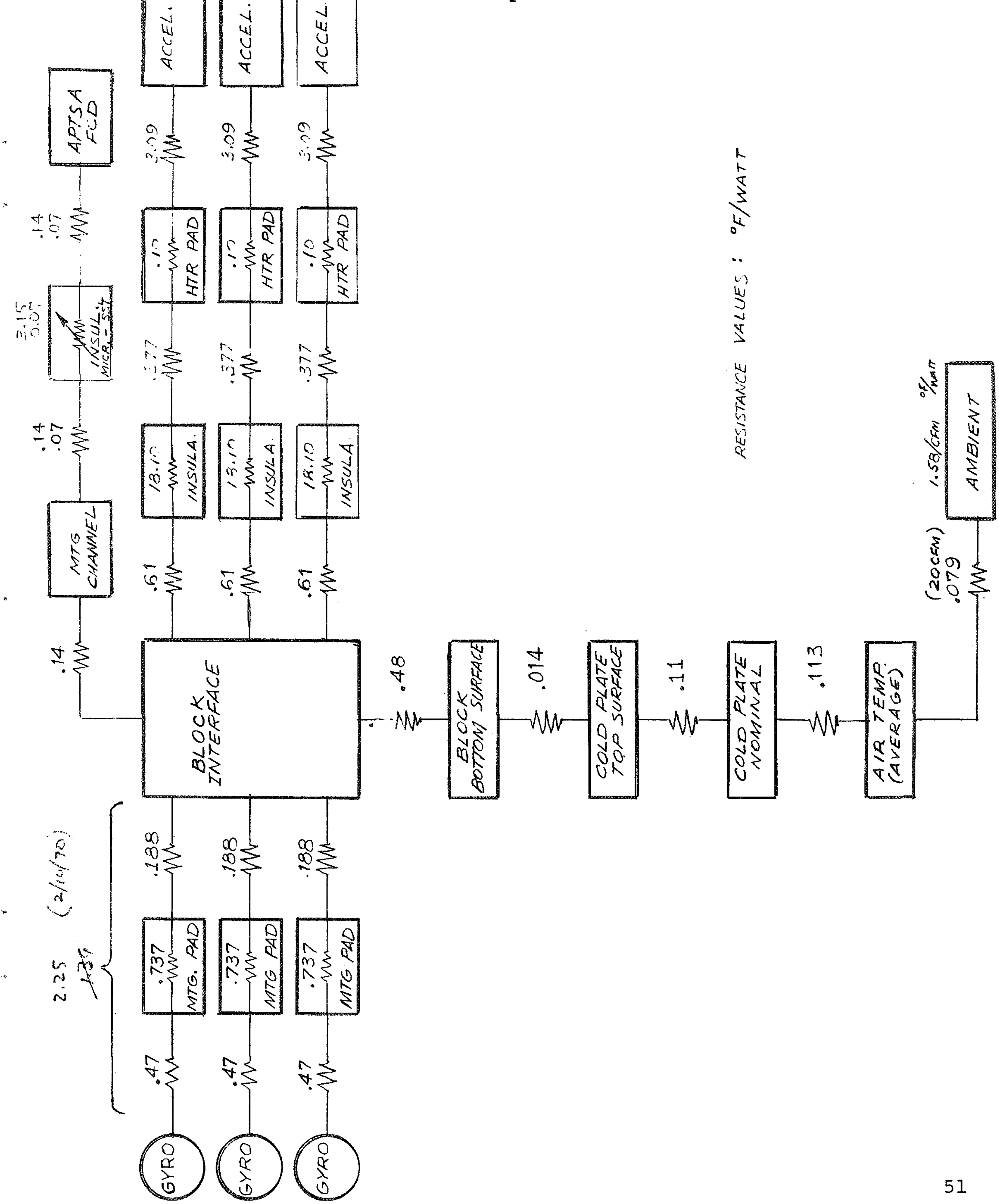
	Ultimate Strength (psi)	Yield Strength (psi)	Elongation (%)	BHN
Typical Properties	33,000	26,000	3	80
Minimum Properties	30,000	22,000	2	75

BY............ DATE 5/20/69 SUBJECT APPENDIX G SHEET NO. 1 OF 6

CHKD. BY............ DATE............ JOB NO............

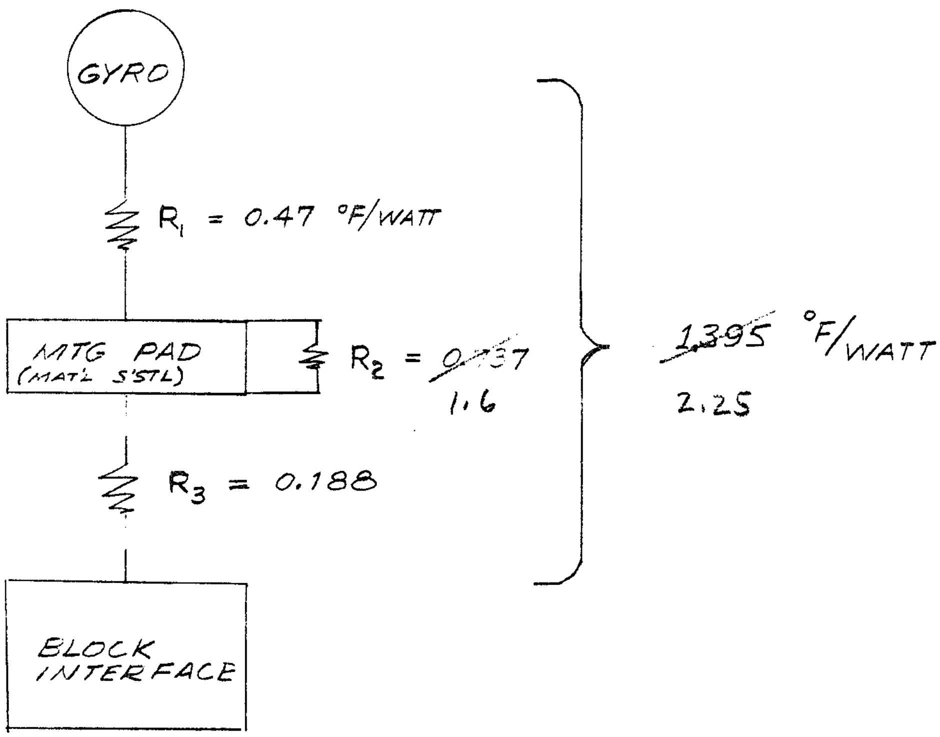
LASER GYRO IMU

Thermal Impedances



SUMMARY: GYRO/IMU BLOCK RESISTANCE

UPDATED VALUES 2/10/70



$$R_1 = \frac{1}{hA} = \frac{1}{1000}\left(\frac{1}{.0072}\right) = 0.1388\ {}^{\circ}F/BTU/HR = 0.47\ {}^{\circ}F/WATT$$

AL TO STL INTERFACE: $h \cong 1000$

$$R_2 = \Sigma \frac{\Delta X}{KA} = \frac{\overset{.500}{\cancel{.187}}\left(\frac{1}{12}\right)}{14(.0072)} + \frac{.187\left(\frac{1}{12}\right)}{14(.018)} = \overset{.413}{\cancel{.155}} + .062$$

$$= \overset{.475}{\cancel{.217}}\ {}^{\circ}F/BTU/HR = \underset{1.6}{\cancel{.737}}\ {}^{\circ}F/WATT$$

$$R_3 = \frac{1}{hA} = \frac{1}{1000}\left(\frac{1}{.018}\right) = .055\ {}^{\circ}F/BTU/HR = .188\ {}^{\circ}F/WATT$$

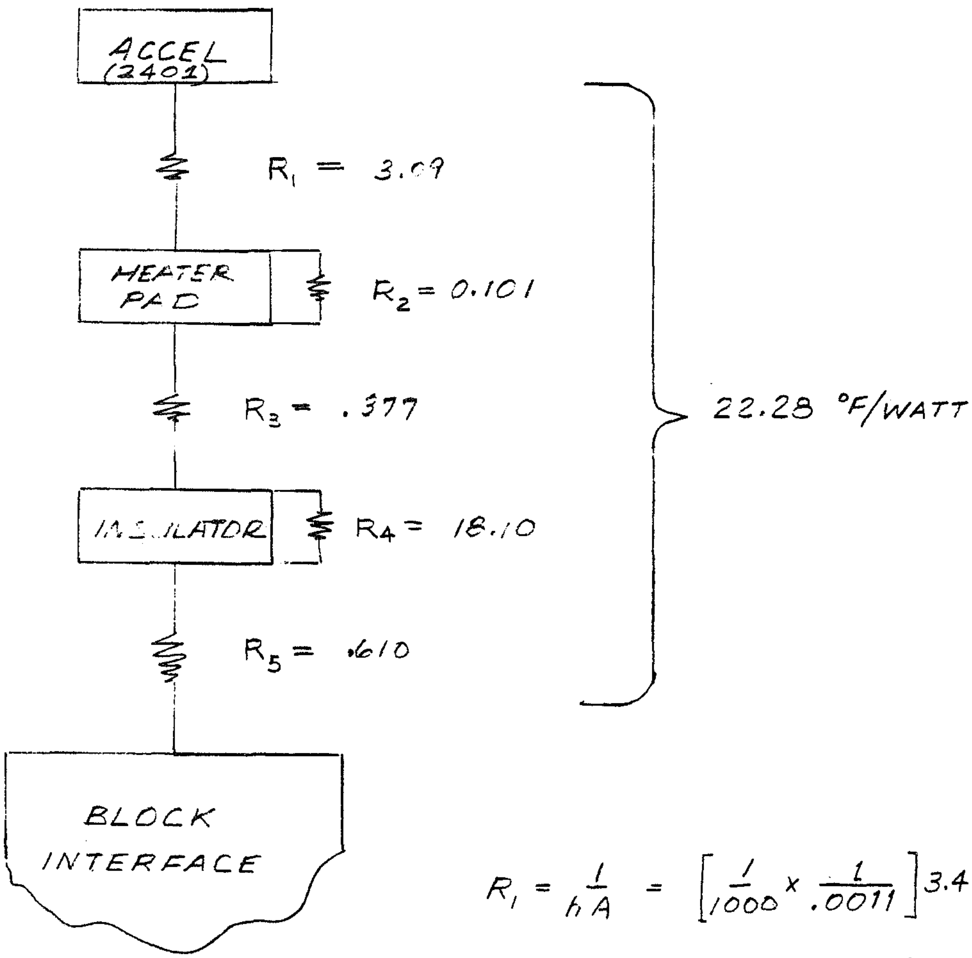
NOTES:

1. SEE DWG C69-2-6 FOR DETAIL OF MOUNTING PAD AND AREA CALCULA.
2. $K_{410\ SSTL} = 14$

BY.......DATE....... SUBJECT....... SHEET NO. 3 OF 6

CHKD. BY.......DATE....... JOB NO.......

SUMMARY: ACCELEROMETER/IMU BLOCK INTERFACE



$$R_1 = \frac{1}{hA} = \left[\frac{1}{1000} \times \frac{1}{.0011}\right] 3.4 = 3.09 \text{ °F/WATT}$$

$$R_2 = \frac{\Delta x}{KA} = \left[\frac{.375 \times \frac{1}{12}}{70 \times .015}\right] 3.4 = 0.101$$

$$R_3 = \frac{1}{hA} = \left[\frac{1}{500} \times \frac{1}{.018}\right] 3.4 = 0.377$$

$$R_4 = \frac{\Delta x}{KA} = \left[\frac{.375 \times \frac{1}{12}}{.234 \times .025}\right] 3.4 = 18.10$$

$$R_{5A} = \frac{1}{hA} = \left[\frac{1}{500} \times \frac{1}{.011}\right] 3.4 = .618$$

$$R_{5B} = \frac{\Delta x}{KA} = \left[\frac{.0025}{.016 \times .012}\right] 3.4 = 42.0$$

$$R_5 = \frac{1}{\frac{1}{.618} + \frac{1}{42.0}} = .610$$

R_{5B} = ACROSS .030 AIR GAP

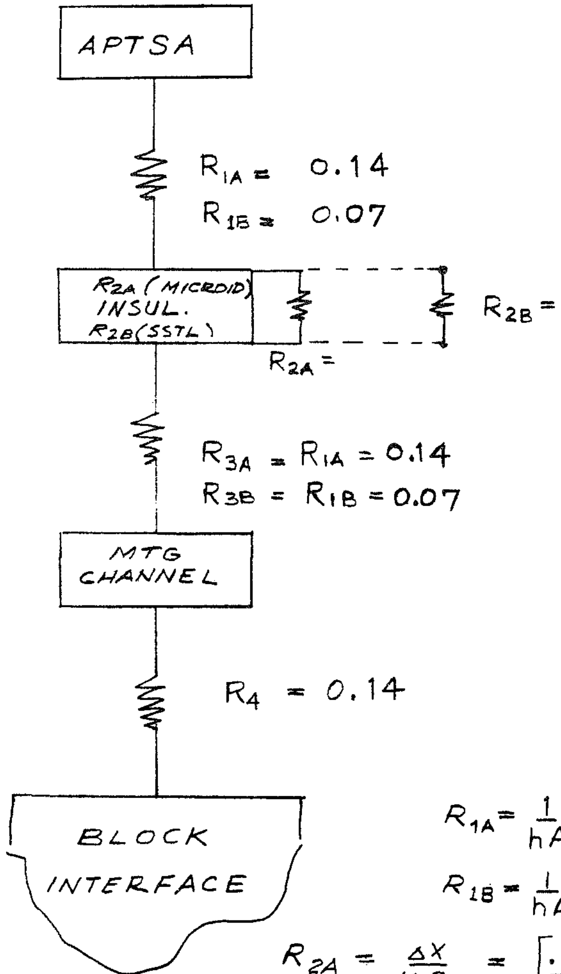
NOTES:

1. HTR PAD SEE DWG. C69-2-5
2. INSULATOR (MICROID -750) " " C69-2-4
3. $K_{2024\text{-}T4} = 70$ BTU/HR(FT²)°F/FT

   $K_{MICROID} = .234$

h = al to al ≅ 1000

h microid to al ≅ 500



$R_{1A} = \frac{1}{hA} = \left[\frac{1}{500(.048)}\right] 3.4 = 0.14$ °F/WATT MICROID

$R_{1B} = \frac{1}{hA} \quad \left[\frac{1}{1000}(.048)\right] 3.4 = 0.07$ S'STL.

$R_{2A} = \frac{\Delta X}{KA} = \left[\frac{.125 \times \frac{1}{12}}{.234\,(.048)}\right] 3.4 = 3.15$ MICROID

$R_{2B} = \left[\frac{.125 \times \frac{1}{12}}{10\,(.048)}\right] 3.4 = 0.07$ S'STL

$R_4 = \left[\frac{1.75 \times \frac{1}{12}}{70\,(.048)}\right] 3.4 = .14$

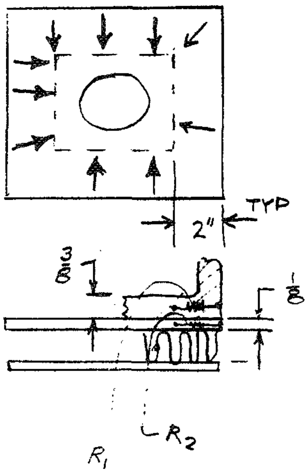
CONTACT AREA REQ'D $7\ IN^2$ SEE SUNUNU'S NOTES

$A = \frac{7}{144} = .048\ FT^2$

NOTE: When block is controlled for min temp (max) gyro insulator is microid (S'STL) since the APTSA's require is constant ambient of 130 ± 5°F

$K_{2024} = 90$

SUMMARY: COLD PLATE TOP SURFACE / COLD PLATE NOMINAL



PERIMETER EFFECTIVE: 15 IN.

$R = \frac{\Delta X}{KA}$

$A_1 = 15 \times \frac{3}{8} = 5.63$

$A_2 = 15 \times \frac{1}{8} = 1.87$

$R_1 = \left[\frac{2/12}{92 \times 5.63}(144)\right] 3.4 = .157\ ^\circ F/WATT$

$R_2 = \left[\frac{2/12}{100 \times 1.87}(144)\right] 3.4 = .436\ ^\circ F/WATT$

$$R_{TOTAL} = \frac{1}{\frac{1}{.157} + \frac{1}{.436}} = 0.11\ ^\circ F/WATT$$

COLD PLATE NOMINAL / AVE AIR TEMP.

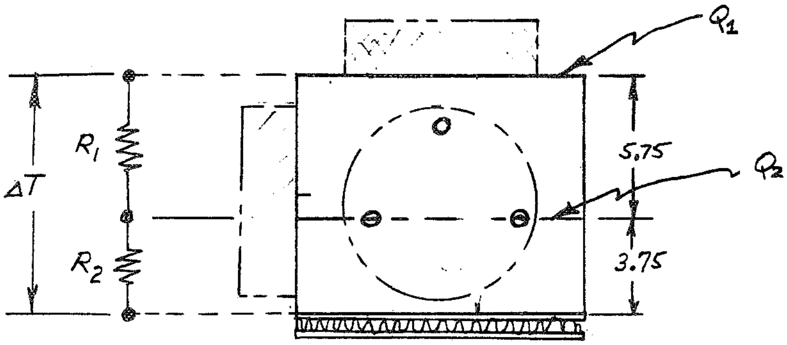
$\Delta T = 3.16 \times \frac{WATTS}{CFM}$

$\frac{^\circ F}{WATT} = \frac{3.16}{2 \times 20} = .079$

BLOWER OUTPUT = 20 CFM

$\Delta T = 2$

SUMMARY: BLOCK INTERFACE / BLOCK BOTTOM SURFACE



		POWER DISSIPATION — WATTS —
GYRO (NOMINAL)	3 x 3 =	9.0
GYRO HTR	3 x 1.3 =	3.9
ACCEL (NOMINAL)	3 x 0.5 =	1.5
" HTR	3 x 2.3 =	6.9
BLOCK HTR (MIN.)	=	2.0
ACCEL ELEC.		12.0
		35.3 W

BLOCK MAT'L. 356-T6
K = 92

$$Q_1 = Q_{ELEC.} + Q_{GY} + Q_{GY-HTR} + 3Q_{ACELL} + Q_{BLOCK} + \frac{1}{3}\left(2Q_{GY} + 2Q_{GY-HTR}\right) + 3Q_{ACELL-HTR}$$

$$Q_1 = 12 + 3 + 1.3 + 1.5 + 2 + \frac{1}{3}(6 + 2.6) + 6.9 = 29.6 \text{ WATTS}$$

$$Q_2 = Q_1 + \frac{2}{3}\left(2Q_{GY} + 2Q_{GY-HTR}\right) = 29.6 + \frac{2}{3}(6 + 2.6) = 35.3 \text{ WATTS}$$

$$\Delta T = R_1 Q_1 + R_2 (Q_1 + Q_2)$$

CROSS SECTION AREA IN R_1, R_2 REGIONS OF BLOCK: (A_1, A_2)

$$A_1 = 7(.56) + 1.7(.50) + 1(.12) + 3(.37) + 6.5(.12) + 3(.3) = 7.68 \text{ IN}^2$$

$$A_2 = 12(.56) + 2.25(.5) + 3(.37) + 4(.12) + 1(.5) + 1.0 = 11.02 \text{ IN}^2$$

CALCULATION OF R_1 and R_2

$$R_1 = \frac{\Delta X}{KA} = \frac{5.72/12}{92 \times 7.68/144} = .097 \ {}^\circ F/BTU/HR = 0.33 \ {}^\circ F/WATT$$

$$\Delta T_1 = 29.6\,(0.33) = 9.77 \ {}^\circ F$$

$$R_2 = \frac{3.75/12}{92 \times 11.03/144} = .044 \ {}^\circ F/BTU/HR = 0.15 \ {}^\circ F/WATT$$

$$\Delta T_2 = 35.3\,(0.15) = 5.29 \ {}^\circ F$$

$$\Delta T = 9.77 + 5.29 = 15.06 \ {}^\circ F$$

$$R = 0.33 + 0.15 = 0.48 \ {}^\circ F/WATT$$

APPENDIX H

Laser IMU

Temperature Control System

Accelerometers

Temperature Set Point (Nominal)	148°F
Temperature Set Point (accuracy)	$\pm$0.1°F
Maximum Power	5 W
Nominal Power	2.4 W
Minimum Power	0.5 W
Heater Power Density (Approx)	9 W/IN^2
Set Point Adjustment Range (from nominal)	$\pm$5°F

Sensor Block Controller

Temperature Set Point (Nominal)	130
Temperature Set Point (accuracy)	$\pm$.0°F
Maximum Power	50 W
Nominal Power	30 W
Minimun Power	1 W
Heater Power Density	3 W/IN^2
Set Point Adjustment Range (from nominal)	+10°/-40°F

Sensor Block Warm-Up

Temperature Set Point (Nominal)	120°F
Temperature Set Point (accuracy)	$\pm$3°F
Maximum Power	750 W
Heater Power Density	10 W/IN^2
Set Point Adjustment Range (from nominal)	+0°F/-40°F

Electronics Plate

Temperature Set Point (Nominal)	128°F
Temperature Set Point (accuracy)	$\pm$1.0°F
Maximum Power	5 W
Power Density	.2 W/IN^2
Set Point Adjustment Range (from nominal)	$\pm$10°F

Environmental Requirements

The TCA electronics shall be capable of operating within specifications in an environment from +30°F to +120°F and from 0-90 percent humidity.

Reliability & Life (Design Goal)

MTBF - 10,000 hours W/O scheduled maintenance at 85°F ambient.

BY........ DATE 5/28/69 SUBJECT........ SHEET NO........ OF........
CHKD. BY........ DATE........ JOB NO........

HEATER POWER REQUIREMENTS

STEADY STATE :

POWER - WATTS

	MAX RATING	MAX NORMAL	MIN. SERVICE
BLOCK	75	36	1.0
ACCELEROMETERS	5	2.4	0.5
GYROS	10	4.2	0.6
ELECTRONICS	5	2.0	0.5

ASSUMING : 5 WATTS/IN^2

$A = \frac{75}{5} = 15 \, IN^2$ REQ'D FOR BLOCK HTRS.

WARM-UP :

ASSUME : 1.) 1 hr is ACCEPTABLE FOR WARMING FROM 70°F TO 140°F

2.) SPECIFIC HEAT (EFFECTIVE) $\cong$ 0.25 BTU/LB °F

3.) SYSTEM WEIGHT = 82 LB

$$Q = mC_p \frac{\Delta T}{\Delta t} = \frac{82 \times .25 \times 70}{1} = 1435 \, \frac{BTU}{HR} = 422 \text{ WATTS}$$

$\therefore$ DESIGN FOR 500 W @ 10 W/IN^2

$$3.4(500) = \frac{82 \times .25 \times 70}{t}$$

$$t(hrs.) = \frac{82 \times .25 \times 70}{1700.0} = .84$$

$$t = 60(.84) = 50.40 \text{ MINUTES}$$

BLOCK			
WARM-UP	POWER	500 WATTS	@ 10 WATTS/IN^2
STEADY-STATE	"	75 "	@ 5 WATTS/IN^2

BY........ DATE........ SUBJECT........ SHEET NO........ OF........
CHKD. BY........ DATE........ JOB NO........

140°F GYRO (70°F AMBIENT)

DESIGN GOAL: 140°F

5.) LET GYRO OPERATE 5°F ABOVE BLOCK

$\therefore$ HTR PWR = 0.6 W

6.) ACCEL.

$\Delta T = 150 - 135 = 15°F$

ΔT (ACCEL/MTG PAD) = 1.5

ΔT (MTG PAD/BLOCK) = 13.5°F

$$Q = \frac{13.5}{19.1} = .706 \text{ W}$$

$Q_{HTR} = .706 - .50 = .21 W$ TOO LOW!

$\therefore$ RUN GYRO 10°F ABOVE BLOCK

$$Q_{GYRO} = \frac{10}{1.39} = 7.2 \text{ W}$$

$\therefore Q_{GYRO\ HTR} = 7.2 - 3.0 = 4.2$ WATT

ACCEL. $\Delta T = 148.5 - 130 = 18.5°F$; block = 130°F

$$Q = \frac{18.5}{19.1} = 0.97$$

$Q_{ACCEL\ HTR} = 0.97 - 0.50 = 0.47$ WATTS

$Q_{SYS.} = 3Q_{GYRO} + 3Q_{ACCEL} + Q_{ELEC} + Q_{BLOCK}$

$3(7.2) + 3(0.97) + 13.3 + Q_{BLOCK}$

$3(7.2) = 21.6$
$3(.97) = 3.0$
13.3
37.9

$\Delta T_{BLOCK/AMBIENT} = 130 - 70 = 60°F$

$$Q = \frac{60}{.796} = 75.4 \text{ WATTS}$$

$\therefore Q_{BLOCK\ HTR} = 75.4 - 37.9 = 37.5$ WATTS

SINCE BLOWER $\Delta T = 0.87°F$

$$\frac{60 - .87}{.796} = 74.2 \text{ W}$$

$74.2 - 37.9 =$ 36.3 WATTS WITH 20 CFM

WITH 5 CFM

$R = .48 + .014 + .11 + .113 + 4(.079) = 1.02$

$$Q = \frac{60 - 4(.87)}{1.02} = 55.4 \text{ W}$$

$55.4 W - 37.9 =$ 17.5 WATTS WITH 5 CFM

BY.................DATE.................. SUBJECT.. SHEET NO.............OF............

CHKD. BY..............DATE.................. .... JOB NO.......................................

.... 103 °F GYRO (70 °F AMBIENT)

ITERATION Nº 1.

DESIGN GOAL : GYRO SET POINT TEMP 95 – 100°F

1.) LET GYRO OPERATE 5 °F ABOVE BLOCK

ASSUME NOMINAL PWR DISSIPATION (GYRO) : 3 W

$$q = \frac{\Delta T}{R} = \frac{5}{1.39} = 3.59 \text{ WATTS}$$

since gyro dissipates 3W:

$$\boxed{\text{HTR. PWR REQ'D}_{(MIN)} = 3.59 - 3.0 = 0.6 \text{ WATTS}}$$

2.) GUESS : BLOCK TEMP. = 93°F ; NOMINAL PWR DISSIPATION : 0.5 W

ACCELEROMETER SET POINT : 150 °F

$\Delta T = 150 - 93 = 57°F$

ΔT (ACCEL. & MTG BLOCK[AL]) = 0.5(3.09) ≅ 1.5°F

ΔT (MTG BLK TO BLOCK) = 57 – 1.5 = 55.5°F

$R_2 = .101$
$R_3 = .377$
$R_4 = 18.10$
$k_5 = .61$
19.088

$$q = \frac{55.5}{19.1} = 2.90 \text{ W}$$

$$\boxed{\text{HTR. PWR REQD (ACCEL)} = 2.90 - 0.5 = 2.4 \text{ WATTS}}$$

3.) APTSA CONTROL AT 130°F ± 5

RUN AT 127°F

$\Delta T = 127 - 93 = 34°F$

R (MICROID)
.14
3.15
.14
.14
3.57

$$q = \frac{34}{3.57} = 9.52 \text{ W}$$

∴ NEED LOWER R SINCE PWR DISSIPATED IS ~ 12 W

$$R_{REQD} = \frac{34}{12.3} = 2.76 \text{ °F/WATT}$$

4.) BLOCK TO HE.

$$Q_{SYS} = \underset{GYRO}{3(3.59)} + \underset{ACCEL}{3(2.90)} + \underset{ELEC}{13.3} + Q_{BLOCK} = 32.7 + Q_{BLOCK}$$

LET $Q_{BLOCK\,(MIN)} = 1.5$ W

∴ $Q_{SYS} = 34.2$ W

R (BLOCK TOP – AMBIENT)
.48
.014
.11
.113
.079
.796

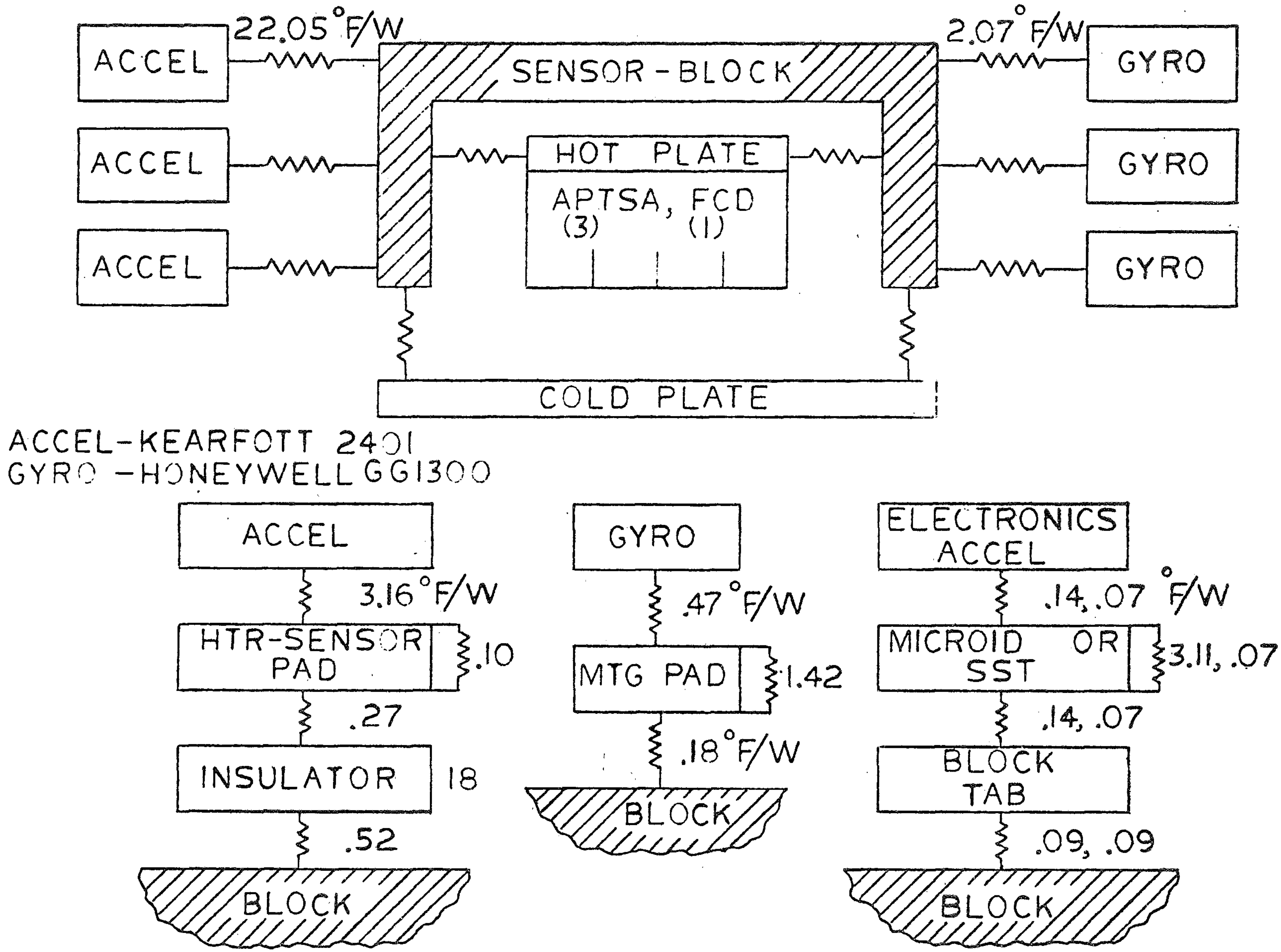
$\Delta T = 34.2(.796) = 27.2$ °F

ΔT due to blower = .079(11) = .87°F

$\Delta T_{TOTAL} = 28$ °F

IF ~~AB~~ AMBIENT IS 70°F BLOCK MUST BE 98°F AND GYRO 103°F

LASER GYRO IMU — (THERMAL CONTROL SCHEME)



IMU THERMAL CONTROL REQUIREMENTS

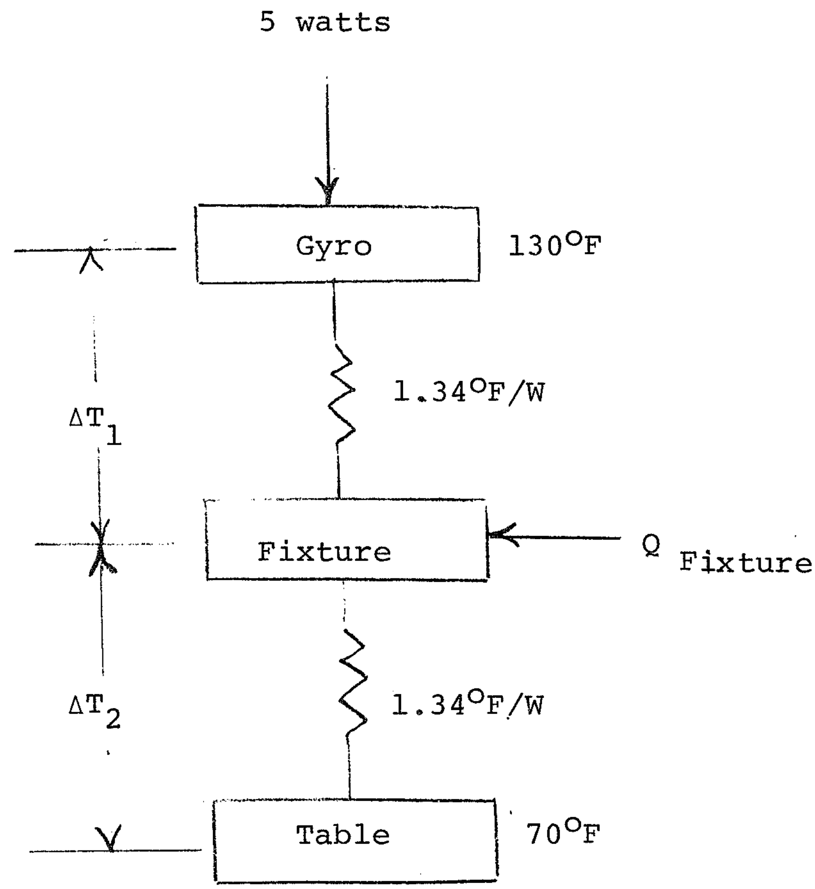
PHASE I; LABORATORY TEST
PHASE II; FLIGHT TEST

SET PT TEMP °F	PHASE I AMBIENT °F	PHASE II (DESIGN CAPABILITY) AMBIENT °F	IMU BLOCK TEMP — °F —	T.C.A. PWR. REQ'D WATTS
T_{GYRO} = 90	70	32 – 70	80	1.83
T_{GYRO} = 140	70	32 – 110	130	1.83
T_{ACCEL} = 150	70	32 – 110	80	3.1
			130	0.48
T_{ELEC} = 130	70	32 – 110	80	3.1
			130	3.1

	IMU BLOCK CONTROL
PHASE I	10W HEATER PLUS DUTY CYCLING FAN
PHASE II	TRADEOFF: INSULATION HTR. PWR DUTY CYCLING FAN

APPENDIX I

Single Unit Test Station for Laser Gyro



$$\Delta T_1 + \Delta T_2 = 5\ (1.34) + (5+Q_F)\ (1.34)$$

$$= 60^{\circ}F$$

$$\therefore\ Q_F = 40 \text{ watts}$$

APPENDIX J

Thermal Losses Through Shroud

The surface area of the shroud will be approximately

$$6 \times 14" \times 14" = 1176 \text{ sq. in.}$$
$$\approx 8 \text{ sq. ft.}$$

The conductivity of the most practical material (urethane foam) is .014 Btu/hr-ft^2-$^{\circ}$F/ft. Thus, the heat loss for one inch of thickness (assuming an average internal temperature of 130°F and an external temperature of 30°F) will be

$$Q = \frac{KA}{\Delta X} \Delta t$$

$$Q = \frac{.014 \times 8 \times 100}{1/12}$$

$$= 134 \text{ Btu/hr}$$

The loss for various thicknesses is shown below

ΔX	Q (Btu/hr)	Q (Watts)
1	134	39
2	67	19
3	45	13
4	33	10

A two inch thickness will provide sufficient thermal resistance to hold the parasitic heat loss to a reasonable level without imposing excessive size requirements on the overall system.

Note that $\frac{K}{\Delta X} = .168$ for even the one inch insulation. This will be the principal resistance since the convection coefficient for the shroud surfaces will be of the order of 1 or 2.

APPENDIX K

Thermal Impedances, SRT/IMU

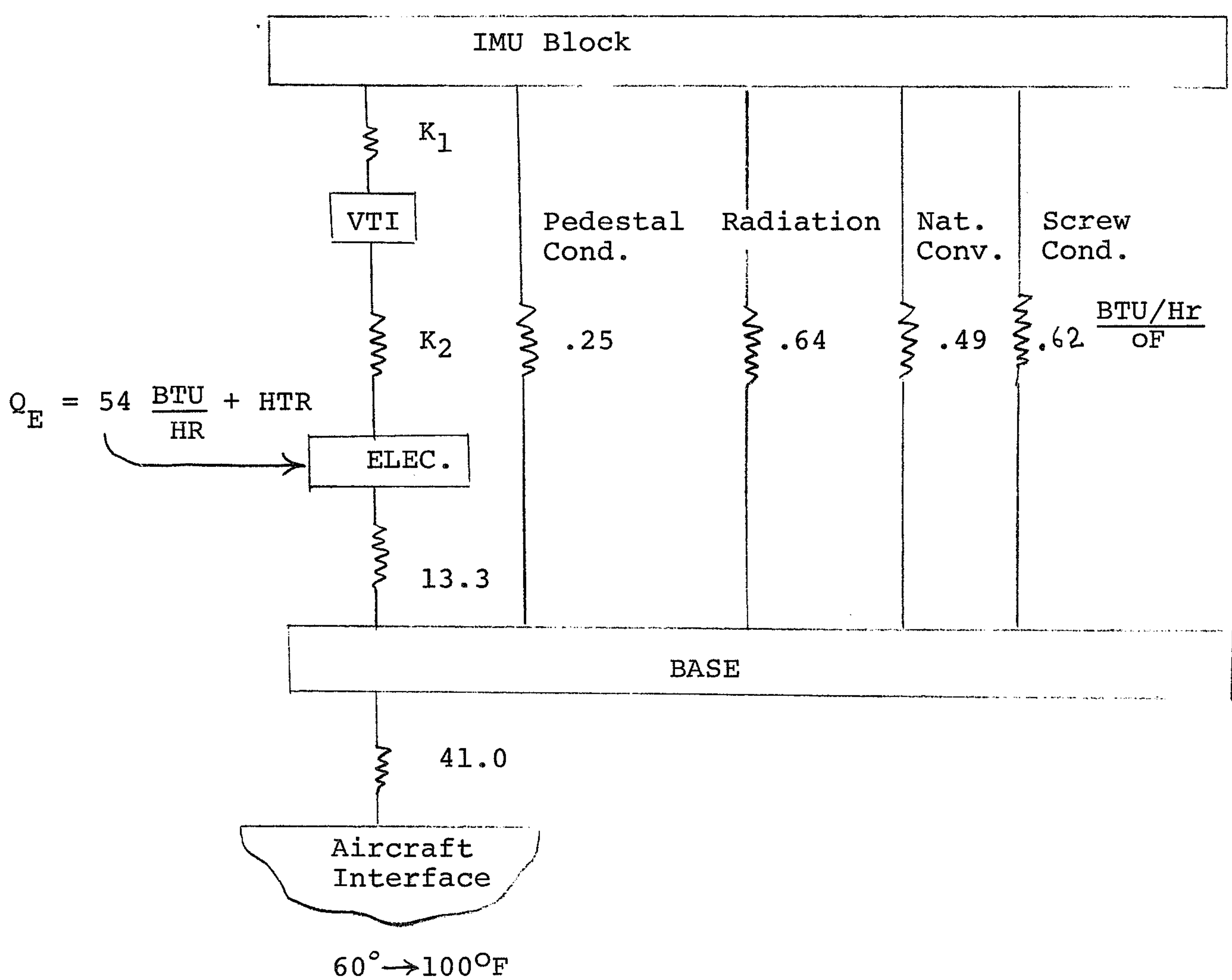
The thermal resistances for this system are based on analysis and experimental data obtained in the oringinal evaluation & at MSL.

Power Budget:

Gyro	6.5W
Gyro Torquer	1.0
Gyro Heater	2.0
Accel.	1.0
	10.5
	x 3
	31.5
Blk. Htr.	4
	35.5

Electronics (UAC estimates)

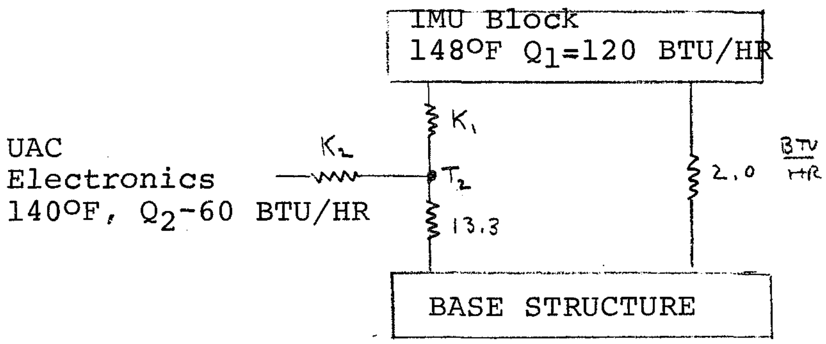
1 FCD @ 3.5W	
3 GPTSA @ 3.1W	15.8W
3 APTSA @ 1.W	



APPENDIX L

Temperature Control of SRT/IMU Electronics

Thermal Resistance and power requirements for electronics of SRT/IMU



CASE I: BASE AT 105°F

$\Delta T \cdot K = Q$

① $(148-105)2 + (148-T_2)K_1 = 120$

② $(148-T_2)K_1 + (140-T_2)K_2 = (T_2-105)13.3$

③ $(140-T_2)K_2 = 60$

③ & ② → ④ $(148-T_2)K_1 + 60 = (T_2-105)13.3$

① $86 + (148-T_2)K_1 = 120$

$(148-T_2)K_1 = 34$

$34 + 60 = 13.3T_2 - 1396.5$ $\qquad T_2 = 112°F$

③ $(140-112)K_2 = 60$ $\qquad K_2 = 2.14 \text{ BTU/HR/°F}$

① $86 + (148-112)K_1 = 120$ $\qquad K_1 = .94 \text{ BTU/HR/°F}$

CASE II: BASE IS AT 65°F; DETERMINE POWER REQUIREMENTS.

⑤ $(148-65)2 + (148-T_2)K_1 = 120 + \Delta Q_1$

⑥ $(148-T_2)K_1 + (140-T_2)K_2 = (T_2-65)13.3$

⑦ $(140-T_2)K_2 = 60 + \Delta Q_2$

SOLVING ⑥ FOR T_2 → $T_2 = 79.6°F$

SOLVING ⑦ FOR ΔQ_2 → $\Delta Q_2 = 69.25 \frac{BTU}{HR} = 20.4$ WATTS

SOLVING ⑤ FOR ΔQ_1 → $\Delta Q_1 = 110.3 \frac{BTU}{HR} = 32.4$ WATTS

APPENDIX M

Thermal Test Plan for the ERSA Strapdown System

This test Plan outlines the basic tasks that should be included in the overall evaluation program of the Breadboard Model of the ERSA Strapdown Inertial Measuring Unit being developed at the NASA Electronics Research Center.

These tests are recommended in order to establish the adequacy and capability of the thermal control system of the ISU. These tests have been selected with the general program objectives in mind, and with an appreciation for the limited extent of the environmental simulation and testing facilities that will be available.

The effort described has been proposed so that a progressive evaluation of the system can be carried out, wherever possible, from the basic component level, through the subsystem and system level. In this manner a general, systematic compilation of all of the significant parameters which determine overall thermal performance can be obtained. Although the sequence of the tests must be coordinated with the overall evaluation program, this plan should serve as a definition of the scope of the testing that will be required.

General

For all of the tests described, the total power dissipated shall be measured, as well as the power requirements of the thermal control components. The thermal environment and the general temperature distribution throughout the system and subsystems shall be monitored (to within $\pm 0.5^{o}F$), and the temperature of the critical points should be tracked to within $0.05^{o}F$, or better.

It is anticipated that a Block Thermal Control Mode and Individual Sensor Thermal Control Modes will be provided in the system. Therefore, whenever applicable, in the subsystem and system sequence of tests the evaluations should be repeated utilizing the Block System alone, the Individual Systems alone, and the Block and Individual Systems in combination. Sufficient data should be taken under these conditions to compare the effectiveness and the control power penalties for each of these thermal control modes.

System Testing

a) The capability of the system to satisfy the steady state temperature control requirements ($\pm$ 0.1°F at the inertial sensors), over the range of possible environmental thermal conditions, shall be evaluated. For a potential range of environmental temperatures from 30°F to 120°F, these tests should be performed at 30°F, 60°F, 90°F, and 120°F. These tests should be performed under various representative levels of inertial control power.

b) The capability of the system to satisfy the temperature control requirements under conditions of a dynamically changing thermal environment should be evaluated. These tests should be performed under various representative levels of inertial control power over a range of environmental temperature change from 30°F to 120°F. The rate of change of the environmental temperature may be constant and should correspond to a mean rate of change of approximately 60°F per hour.

This series of tests should be repeated for an environmental temperature change from 120°F to 30°F.

The tests described in a) and b) above should be repeated with only five of the six inertial control channels operative. This will permit evaluation of the effect of the loss of power dissipation from one of the channels on the capabilities of the thermal control system to regulate the temperature of the five remaining channels.

c) The effect of other potential system malfunctions should be simulated by means of power sources (heaters) and sinks (cold plates, etc.) to determine the capability of the thermal control system to respond to adverse situations. The conditions for these tests should correspond as closely as possible to the potential conditions which may exist at the time of the failure, using data available from the component manufacturer.

Subsystem Testing

a) The Sensor Block subsystem assembly should be tested with dummy (thermal) inertial sensors in order to generate a preliminary temperature map and in order to evaluate or confirm the thermal resistances of this subsystem.

b) The transient thermal response of this subsystem should be tested under various conditions of transient power dissipation to generate design and performance data for the principal thermal capacitances of the subsystem.

c) A single position sensor block mockup should be assembled and evaluated to determine the temperatures and temperature gradients at the sensor block-adapter interface.

d) A similar mockup should be utilized to test and compare the relative design merits of various sensor mounting bracket and adapter designs. In particular the effect of these designs on the temperature profile of the inertial sensors should be evaluated in order to determine their overall effect on the temperature control capability of the completed system.

Component Testing

The principal individual components involved in the thermal control of the ISU which should be evaluated separately include the Temperature Control Amplifiers, the Gyros, the Accelerometers, and the principal thermal resistance module.

a) The Temperature Control Amplifiers should be tested in order to verify performance parameters such as long term stability, thermal stability, standby power requirements, efficiency, and sensitivity.

b) The Accelerometers and Gyros should be evaluated under a variety of thermal conditons (temperature, temperature gradients, etc.) to confirm or determine the effect of temperature profiles on the sensor control parameters such as Bias, Scale Factor, Sensor Stability, Mass Unbalance, etc. These results should be used to determine exactly what requirements must be placed on the thermal control systems to achieve the required overall system performance.

c) The principal thermal resistance between the inertial sensors and the environment will determine the power requirements of the thermal control systems. Although there is a definite advantage in utilizing a variable thermal resistance, this is such a critical area in the design of the thermal control system that any such concept should be evaluated individually in order to obtain complete performance data, before incorporating any approach into the subsystem or system level.